ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF
ECONOMIC GEOLOGISTS

VOL. 45 AUGUST, 1950 No. 5

URANINITE IN THE COEUR D'ALENE DISTRICT, IDAHO.

ERNEST E. THURLOW AND ROBERT J. WRIGHT.

ABSTRACT.

Trace amounts of uraninite occur in the lower levels of two silver-base-metal producers in the Coeur d'Alene district, Idaho. For the most part, the uranium-bearing veinlets follow small structures in the quartzite wall rock of the major ore bodies. The radioactive veinlets are bordered by a zone of red stained quartzite.

The ores are characterized by tetrahedrite, pyrite, arsenopyrite, and chalcopyrite in a siderite-quartz gangue. Uraninite forms small spherulites that replace vein quartz, quartzite wall rock, and (to a lesser extent) tetrahedrite. Observations to date suggest that uraninite was deposited in the late stages of ore deposition.

Ore deposits of the Coeur d'Alene district have certain features in common with the great pitchblende producing veins of the world.

INTRODUCTION.

A NEW occurrence of uraninite was discovered in July 1949 during a radiometric examination of the Sunshine mine in the Coeur d'Alene mining district of Idaho. The Sunshine mine, a leading silver producer, was selected for examination by the exploration staff of the Atomic Energy Commission on the basis of geologic and mineralogic favorability for the occurrence of uranium.

Following the Sunshine discovery, but prior to a general reconnaissance of all mines in the area, uranium was found in the Coeur d'Alene mine, also on the basis of geologic favorability. This mine, which is located about 2 miles east of the Sunshine mine, was selected for examination because of a reported abundance of cobalt "bloom" associated with one of the veins. The cobalt-uranium association has been accepted in the past as a useful guide in the search for primary uranium ores.

It is estimated that nearly fifty miles of underground workings in the district have been examined radiometrically by Commission and company geologists. No uraninite has been found in mines other than the two here described, although considerable reconnaissance remains yet to be done.

This is a preliminary report on geologic and mineralogic data obtained thus far from the two known occurrences. It is hoped that the present paper

will stimulate further geologic studies and radiometric investigations of mineral deposits elsewhere, particularly those having features similar to the ones described here.

ACKNOWLEDGMENTS.

It would be difficult to list here all of the persons who have been helpful in this investigation of the uranium possibilities of the Coeur d'Alene mining district. Without exception everyone from miners and prospectors to general managers and mine presidents, and particularly the geologists and engineers, has given his whole-hearted support. The complete cooperation of all companies concerned was essential, and the response and interest shown have made it possible to prepare a preliminary report at this time.

The entire staffs of the Sunshine Mining Company and the Coeur d'Alene Mines Corporation have aided and encouraged the study of the uranium occurrences. R. D. Leisk, General Manager of the Sunshine Mining Company, has shown a keen interest in the investigations and has directed a thorough program of exploration by his geological staff. Raymond F. Robinson, Chief Geologist of the Sunshine Mining Company, and T. E. Gillingham, Geologist for Bunker Hill and Sullivan Mining and Concentrating Company, accompanied E. E. Thurlow when the uranium-bearing material was discovered in the Sunshine mine. Dr. H. C. Mowry, President of Coeur d'Alene Mines Corporation, has been cooperative in every way.

Through Professor Paul F. Kerr of the Department of Geology at Columbia University, the first positive identification of the principal uranium mineral as uraninite was made. Further mineralogic and petrographic studies are being conducted for the Atomic Energy Commission under the supervision of Professor Kerr. The photomicrographs were prepared through the courtesy of American Cyanamid Research Laboratories, Stamford, Connecticut.

The encouragement and support of Dr. P. L. Merritt, Assistant Manager of Raw Materials Operations, is deeply appreciated.

LOCATION.

The Coeur d'Alene mining district is centered about the towns of Kellogg, Osburn, and Wallace, Idaho. The district has accounted for more than a billion dollars in metal value production, a distinction shared by only seven other mining districts in the world. It is situated in Shoshone County about 75 miles east of Spokane, Washington, in rugged mountainous country. The area of particular interest in this report lies in the western part of that portion known as the Silver Belt (Figs. 1, 4). The Silver Belt as now accepted extends more than six miles in an east-west direction and attains a width of about 3 miles. It is bounded on the north by the Osburn fault and on the south by the Big Creek fault.

GENERAL GEOLOGY OF THE COEUR D'ALENE DISTRICT.

The general geology of the Coeur d'Alene district has been well described [1] and only a brief summary is included here. The district is underlain by Pre-

[1] Ransome, F. L., and Calkins, F. C., The geology and ore deposits of the Coeur d'Alene district, Idaho: U. S. Geol. Survey Prof. Paper 62, 203 pp., 1908.

cambrian quartzites, argillites, and impure limestones of the Belt Series. These rocks have been intensely folded and faulted and intruded by monzonitic stocks presumably related to the Idaho batholith. Diabase and lamprophyre dikes of somewhat varied composition cut the sedimentary series.

Calkins divided the Belt Series, which in the Coeur d'Alene district probably exceeds 20,000 feet in thickness, into six formations which he named,

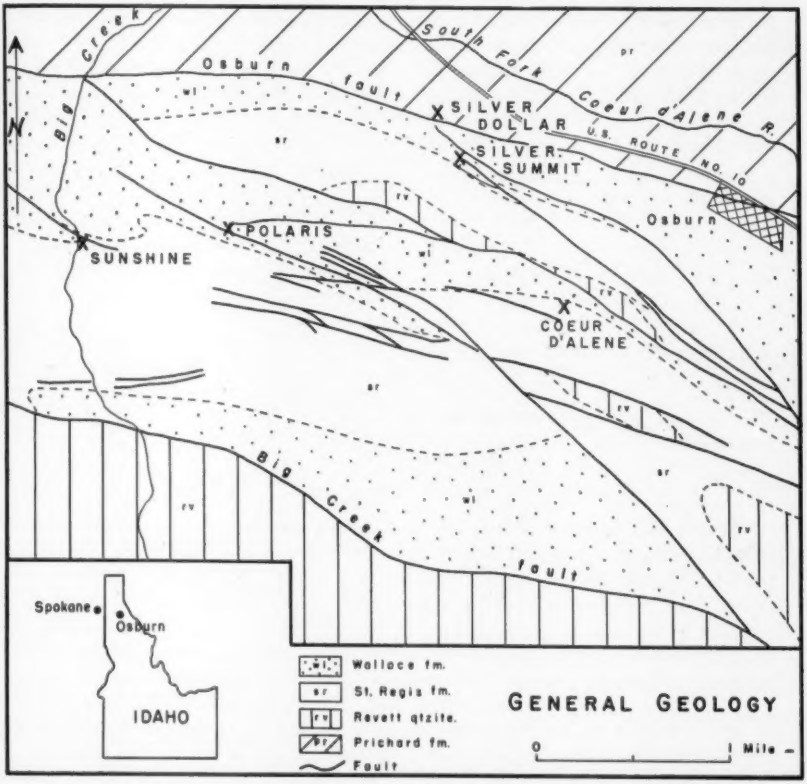

FIG. 1. General geology, west end of the Silver Belt (after Shenon and McConnel, Idaho Bur. Mines and Geology Pamph. no. 50).

from oldest to youngest, the Prichard, Burke, Revett, St. Regis, Wallace, and Striped Peak. Of these, only the Revett, St. Regis, and Wallace are exposed in the Silver Belt. The St. Regis has been the most productive ore-bearing formation in the Silver Belt, and uraninite-bearing veins thus far discovered appear to lie wholly within this formation. It is composed principally of thin-bedded, purplish-gray quartzites and argillites with some massive quartzite members. The formation has a thickness of 1,000 to 1,400 feet.

It was recognized by Ransome and Calkins that the alteration of the Belt formations consists primarily of the "thorough filling-in of original pore spaces with quartz and sericite and the principal agent in this process was hot circulating water." [2] It has only been in recent years, however, that this concept has taken on economic significance, and it is now recognized [3] that all of the important ore deposits lie within zones that have been highly sericitized, with a resultant "bleaching" effect. Bleached rocks are considered favorable hosts for ore deposits in the district as the bleaching process appears to be one of the earlier manifestations of mineralization. Several well defined zones of such alteration attaining widths of as much as one-half mile are found in the Silver Belt, and bleached quartzites of the St. Regis formation are the host rocks for the uranium-bearing veins. Within these zones all of the rocks are sericitized and altered to a light color.

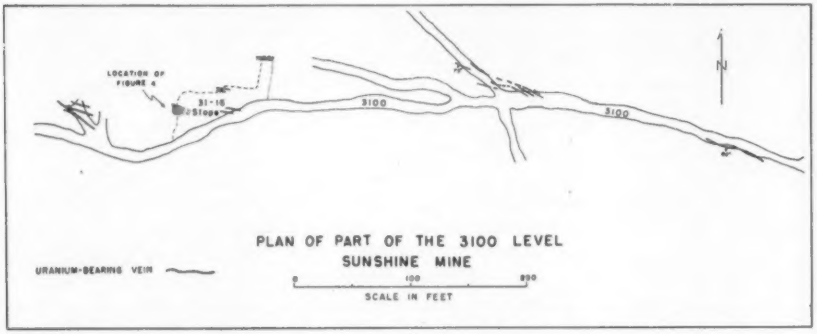

FIG. 2. Part of the 3100-level, Sunshine mine, showing location of uranium-bearing veins. The main Sunshine vein is followed by the 3100 drift. (Courtesy of Sunshine Mining Co.)

THE SILVER BELT.

The Belt formations of the Silver Belt have been complexly folded and faulted. One of the prominent structural features is the overturned Big Creek anticline (Fig. 4), the north (over-turned) limb of which is the locus of most of the known ore deposits of the Silver Belt. The Osburn fault, which places the Prichard formation on the north adjacent to the Wallace on the south, is the dominant structure of the Coeur d'Alene district. It forms the northern boundary of the Silver Belt and separates areas with contrasting ores and structures. Except for the Big Creek and Fort Wayne faults, all of the faults shown (Fig. 4) have normal displacement and all dip south at steep angles. Vertical displacements range from a few hundred feet to possibly more than

[2] Ransome, F. L., and Calkins, F. C., op. cit., p. 75.

[3] Sorenson, Robert E., Deep discoveries intensify Coeur d'Alene activities: Eng. and Min. Jour., vol. 148, no. 10, pp. 70–78, Oct. 1947.

Shenon, P. J., and McConnel, R. H., The silver belt of the Coeur d'Alene district, Idaho: Idaho Bur. Mines and Geology Pamph. no. 50, May 1939.

15,000 feet along the Osburn fault. The horizontal movement of the Osburn fault has been variously estimated from a few thousand feet to several miles.

The known ore deposits of the Silver Belt are found within broad shear zones which cut beds of the Wallace and St. Regis formations on the north limb of the overturned Big Creek anticline. These shear zones do not parallel the major faults but form angles of 20 to 30 degrees with them and are apparently the result of differential movement along the faults. Fracture cleavage, recognized as an important structural feature in the district,[4] locally controlled the mineralizing solutions. In general, the veins strike nearly east-west and most of them dip south at angles of 60 to 80 degrees. There is some evidence of slight post-mineral movement along the veins, and in the Sunshine mine a few cross-faults offset the vein as much as 15 feet.

Argentiferous tetrahedrite (freibergite) and galena are the principal ore minerals. The accessory metallic minerals include pyrite, arsenopyrite, chalcopyrite, stibnite, sphalerite, boulangerite, bournonite, specularite, and gersdorffite.[5] Iron and manganese oxides are prominent oxidation products, and secondary copper and lead minerals are common in near-surface workings. Erythrite has been noted in several mines and appears to form soon after workings are opened. No primary cobalt-bearing mineral has been identified except gersdorffite, which has been reported to contain up to 14 percent cobalt.[6] Siderite is the most common gangue mineral and in places occupies the veins almost to the total exclusion of other minerals. Ankerite and quartz are also abundant and barite has been noted.

RADIOACTIVE VEINS.

Coeur d'Alene Mine.

In the Coeur d'Alene mine known radioactive material is confined to two weakly mineralized, highly silicified zones adjacent to the North vein. At present, the significance of this occurrence is primarily that, when considered with the Sunshine mine, it indicates uranium mineralization had a lateral range of at least two miles. Also, it lends further weight to the uranium-cobalt association as a guide in finding uranium ore, notwithstanding the fact that erythrite is found elsewhere in the district apparently unaccompanied by uranium.

Sunshine Mine.

General Features.—In the Sunshine mine uraninite has been found in veins exposed by several of the deeper workings. The uraninite appears not primarily within the main Sunshine vein but rather in veins that occupy inde-

[4] Shenon, P. J., and McConnel, R. H., Use of sedimentation features and cleavage in the recognition of overturned strata: Econ. Geol., vol. 35, pp. 430–444, 1940.

[5] Willard, Max E., Mineralization at the Polaris mine, Idaho: Econ. Geol., vol. 36, pp. 539–550, 1941.

Anderson, Richard J., Microscopic features of ore from the Sunshine mine: Econ. Geol., vol. 35, pp. 659–667, 1940.

[6] Reported in Palache, C., Berman, H., and Frondel, C., Dana's system of mineralogy, vol. 1, p. 299, John Wiley and Sons, New York, 1944.

pendent but closely related structures.[7] There is a decided preference for the foot (north) wall of the Sunshine shear system, although some uranium has been found in the hanging wall of the vein (Fig. 2). The width of the uranium-bearing veins is variable but rarely exceeds 18 inches, and in places radioactivity is found along black paper-thin seams. Locally the veins are numerous and closely spaced, forming broad mineralized zones (Fig. 3). Present observations indicate that within the mineralized zones uranium-bearing shoots may be expected to be irregular and highly variable in grade.

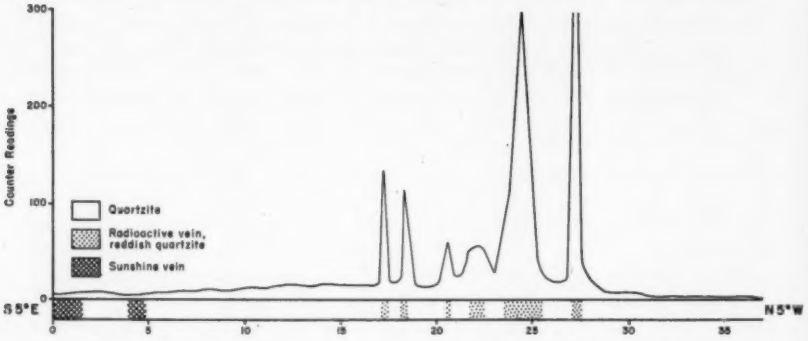

FIG. 3. Radiometric traverse, west end of the 31–16 stope, Sunshine mine. Readings by field model Geiger counter with the probe held at the rock face.

In general, the uranium-bearing veins lie parallel to the strike of the bedding and are mainly controlled by fracture cleavage. In contrast, the Sunshine vein is localized primarily along a shear zone with little regard for bedding or cleavage. The predominant strike of the uranium zones is nearly east-west, although uranium-bearing veins striking approximately north-south have also been observed. In places these veins appear to intersect the Sunshine vein, but structural evidence of age relations is lacking in present exposures. The restriction of uranium-bearing material to well defined veins independent of the Sunshine vein suggests that the uranium may have been introduced during a separate mineralization epoch; on the other hand, it may be possible that the Sunshine vein structure was closed at the time uraninite, a late mineral, was deposited from the ore solutions.

Unfortunately, present exposures of the radioactive zones in the Sunshine mine are almost everywhere obscured by secondary products resulting from years of post-mine oxidation. Especially characteristic of those veins containing significant amounts of uraninite, however, is the presence of a reddish staining of the adjacent wall rock. The red coloration is thought to be due to finely disseminated hematite.

[7] The concentration of uranium ores along fractures related to major fault zones is characteristic also of certain Canadian deposits. James, W. F., Lang, A. H., Murphy, R., and Keston, S. N., Canadian deposits of uranium and thorium: Min. Eng., vol. 187, p. 242, 1950.

FIG. 4. Structural elements of part of the Silver Belt. Aerial photograph copyrighted by Scamahorn, Spokane.

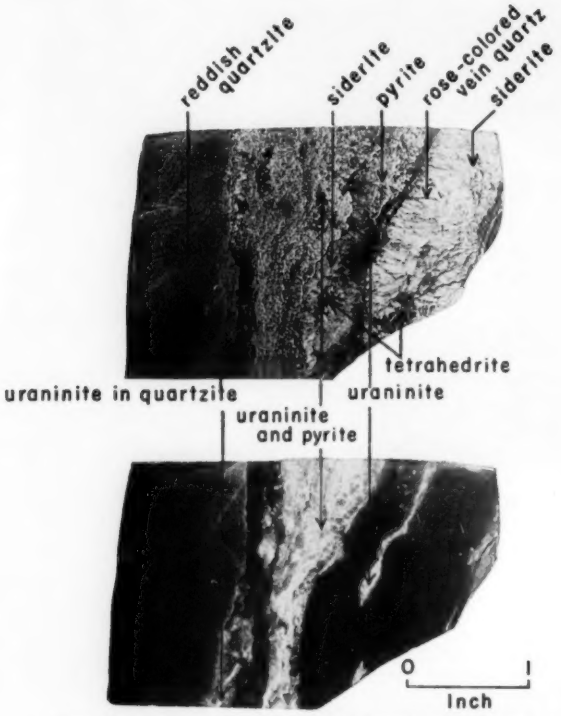

FIG. 5. Photograph and autoradiograph of radioactive veinlet, 31-16 stope Sunshine mine.

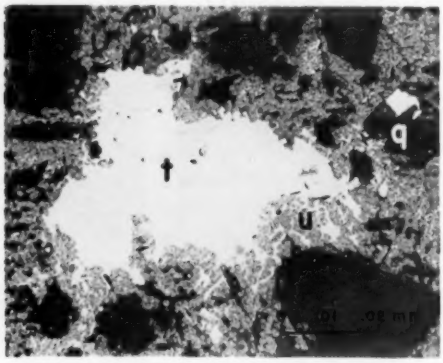

FIG. 6. Marginal replacement of tetrahedrite (t) grain by spherulitic uraninite (u). Magnification X 750.

Mineralogy.—The mineralogy of the uranium-bearing veins is similar to that of the copper-silver ores of the Sunshine mine, and this suggests a common period of mineralization. The mineral assemblage is comparatively simple with pyrite, tetrahedrite (freibergite variety) and arsenopyrite as the dominant metallic minerals. The gangue is primarily brown siderite, cut by minute veinlets of rose-colored glassy quartz. Tetrahedrite is the most common metallic mineral within the siderite. The other minerals—pyrite, arsenopyrite, and uraninite—may occupy the center portion of a vein but more commonly are found along the vein margins and within the adjacent wall rock (Fig. 5). In some specimens uraninite forms narrow parallel veinlets cutting massive sulphides.

Observations to date indicate that the uranium-bearing veins contain a higher percentage of pyrite and arsenopyrite than the copper-silver ores. Certain of the uranium-bearing zones are low in tetrahedrite. In this connection it may be significant that in the Erzgebirge region of Czechoslovakia uranium minerals were recognized for years as "ore robbers," for wherever pitchblende increased in quantity the silver content decreased. This characteristic may be related to vertical zoning in the deposits, a possibility that is discussed in a later section.

Under the microscope pyrite appears to be the oldest of the metallic minerals. It is found within the vein quartz, along the margins of siderite masses, and in the quartzite wall rock as well. Arsenopyrite is fairly common, in the form of euhedral crystals which commonly border pyrite masses; this marginal position suggests that arsenopyrite is the younger. Both the pyrite and arsenopyrite are cut by replacement veinlets of tetrahedrite, and the siderite also is commonly replaced by tetrahedrite masses, the outlines of which are generally determined by the siderite cleavage planes. Chalcopyrite is present only in minor amounts, and it forms small bodies along the edges of tetrahedrite masses. Minor galena has been seen in hand specimen, and stibnite, a mineral not hitherto described from the ore, was identified in several hand specimens of wall rock and vein matter. Its relation to the other minerals is not clear.

The microscopic evidence indicates that the sequence of sulfide deposition was: pyrite, arsenopyrite, tetrahedrite, chalcopyrite. The observed paragenesis is in accord with that reported for the Sunshine copper-silver ore and for the ore of the Polaris mine.[8]

The primary uranium-bearing mineral has been identified by X-ray powder methods at Columbia University as uraninite. Secondary yellow and orange uranium minerals are present in minor amounts. These have formed at the expense of uraninite, presumably since mine development.

The uraninite occurs primarily as a replacement of quartz, within which it typically forms small spherules averaging about 10 microns in diameter. The spherules occur in more or less compact groups, and in places are joined into threads which are irregular or form circular and arc-like outlines (Figs. 7, 10). Elsewhere the spherules are not in evidence; either they have enlarged and coalesced so that their identity is lost or else the uraninite originally crystal-

[8] Willard, op. cit., p. 548, and Anderson, op. cit., pp. 663–666.

lized in more massive form. Where the replacement of quartz by uraninite is slight, the uraninite outlines the edges of the quartz grains (Fig. 7). Where replacement has been more complete the uraninite threads have thickened at the expense of the quartz grains (Fig. 8), until at the most advanced stage of replacement an irregular meshwork of uraninite surrounds small isolated unreplaced areas of quartz, sericite, and other minerals (Fig. 9).

The relative age of the uraninite with respect to the other metallic minerals has been established with respect to tetrahedrite and quartz, both of which are replaced by uraninite (Figs. 10, 11, 12). Since uraninite replaces tetrahedrite, one of the latest metallic minerals, it appears that uranium mineralization occurred during the late stages of vein deposition. Chalcopyrite, too, appears to be later than tetrahedrite, but the age relation between uraninite and chalcopyrite is yet to be determined. It is perhaps significant that uraninite is intimately intergrown and contemporaneous with chalcopyrite in the ores of Gilpin County, Colorado.[9] In the Cornwall district of England, too, pitchblende is closely associated with and crosscuts copper ores, indicating that pitchblende is later than chalcopyrite.[10] At other localities, on the other hand, the evidence suggests that pitchblende is earlier: at Great Bear Lake, Canada, pitchblende precedes tetrahedrite, chalcopyrite, galena, and sphalerite,[11] and the uraninite at Shinkolobwe, Belgian Congo, precedes both chalcopyrite and pyrite.[12]

Siderite is the most abundant gangue mineral and is, for the most part, an early mineral. Still, in only a few of the polished surfaces examined to date is there a suggestion that uraninite is in contact with siderite. Almost exclusively the uraninite replaces quartz (Fig. 10) although, to a lesser extent, it also replaces tetrahedrite. Where quartz and siderite are intimately intergrown, the selective replacement of quartz is quite striking (Fig. 11). The uraninite-quartz association is developed on a microscopic scale and is not readily apparent in hand specimen. Vein quartz, which provides the host for part of the uraninite, appears to be later and much less abundant than the veinlets of rose-colored quartz that are common within the siderite. The preferential replacement of quartz by pitchblende has been observed also in a recent study of ores from the Caribou mine, Boulder County, Colorado.[13]

The association of spherulitic pitchblende with vein quartz at Great Bear

[9] Bastin, E. S., and Hill, J. M., Economic geology of Gilpin County and adjacent parts of Clear Creek and Boulder Counties, Colorado: U. S. Geol. Survey Prof. Paper 94, p. 124, 1917.

[10] Stephens, F. J., Ores of uranium in West Cornwall and Scandinavia: Roy. Cornwall Polytech. Soc., Ann. Rept., vol. 74, pp. 70–81, 1906.

[11] Kidd, D. F., and Haycock, M. H., Mineragraphy of the ores of Great Bear Lake: Geol. Soc. America Bull., vol. 46, p. 933, 1935.

[12] Thoreau, J., and Trieu de Terdonck, R., Le Gite de Shinkolobwe, Koslo: Institut Colonial Belge, Sec. des Sci. Nat. et Med., Tome II, 46 pp., 133; Geol. Soc. America Bull., vol. 46, pp. 941–942, 1935 (English abstract).

[13] Wright, H. D., Columbia University, personal communication.

FIGS. 7–9. Progressive replacement by uraninite.

FIG. 7. Partial replacement of quartz (q) and tetrahedrite (t) by uraninite (u).

FIG. 8. More complete replacement of quartz (q) by uraninite (u).

FIG. 9. Advanced replacement of quartz (q) and other minerals by uraninite.

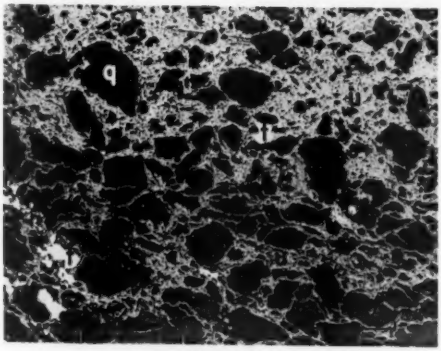

FIG. 7

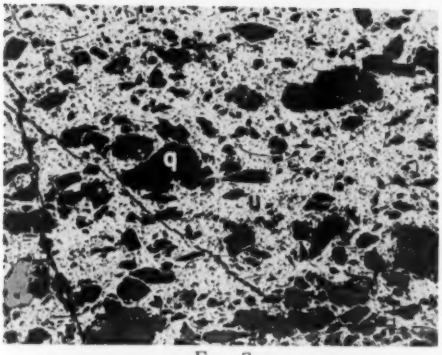

FIG. 8

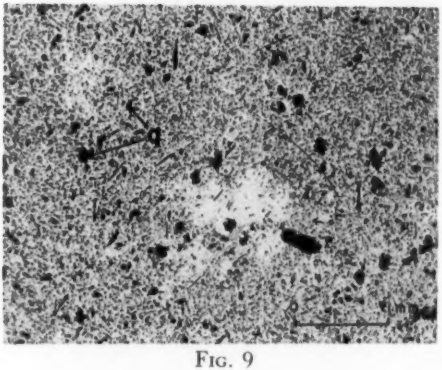

FIG. 9

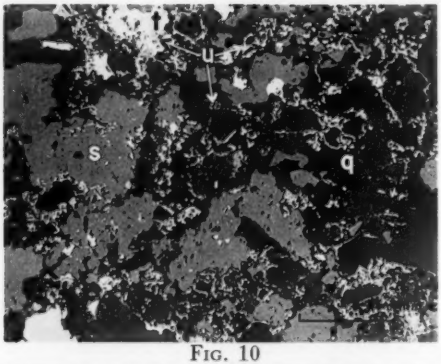

FIG. 10

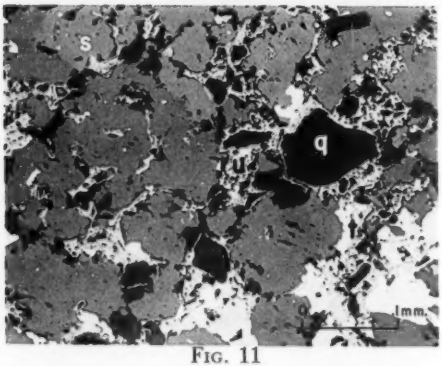

FIG. 11

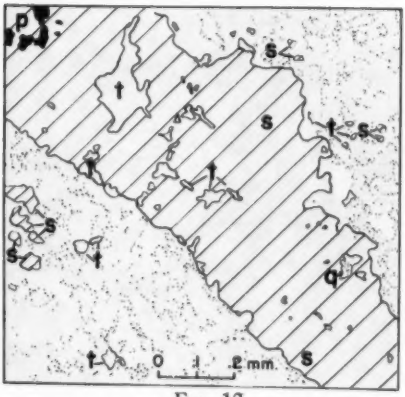

FIG. 12

Lake has been taken to indicate contemporaneous deposition of both minerals from a gel.[14] In the Sunshine mine it is evident that colloidal silica is not required for the formation of uraninite spherules because spherulitic uraninite replaces tetrahedrite and the quartzite wall rock as well as vein quartz.

Wall Rock Coloration.—The wall rock of the uranium-bearing veins is bleached St. Regis formation—here a gray-white quartzite. A persistent and striking feature of the radioactive veins in the Sunshine mine is the reddish coloration of the adjacent quartzite. All observations to date indicate that this envelope of coloration is uniquely associated with the uranium-bearing veins; it is not known elsewhere in the mine, and all veins with significant radioactivity are bordered by red-stained wall rock. The zone of alteration varies from a fraction of an inch up to a foot in width. Near the vein the quartzite is colored brownish red and the intensity of color decreases away from the vein, merging gradually into white or gray quartzite. The reddish wall rock is locally described as "jasper," a term which is convenient but not strictly applicable since the coloration has been superposed on the St. Regis quartzite.

The reddish coloration of the quartzite bordering radioactive veinlets is quite diffuse in thin section. It originates primarily in association with the fine-grained sericite which is interstitial to the quartz grains. Here tiny grains and blades of a blood-red mineral, presumed for the present to be hematite, can be seen. Chemical analyses have been made of pink altered wall rock and uncolored quartzite to indicate whether oxidation of ferrous iron already present in the quartzite has taken place or whether ferric iron has been added to the rock. Results to date are, however, inconclusive.

In addition to the reddish coloration of wall rock, the quartz that forms tiny veinlets in vein siderite is typically rose-colored. The origin of this coloration in vein quartz and its relation to reddish quartzite wall have not been determined. The whole general problem of the red coloration and its relationship to uranium-bearing solutions is currently under consideration by geologists of the Atomic Energy Commission.

Possibility of Vertical Zoning.—Whether or not more intense uranium mineralization can be expected in undeveloped parts of the Silver Belt, perhaps in depth, is a matter of conjecture. The occurrence of pitchblende in submicroscopic spherules is recognized at Great Bear Lake as indicating deposition from solutions comparatively lean in uranium oxide.[15] The fact that uraninite in the Coeur d'Alene district has been found only in deeper mine workings might be explained on the basis of vertical temperature zoning. At Jo-

[14] Kidd, D. F., and Haycock, M. H., op. cit., p. 899.
[15] Kidd, D. F., and Haycock, M. H., op. cit., p. 899.

FIGS. 10–12. Selective replacement (black areas are holes).

FIG. 10. Selective replacement of quartz (q) and tetrahedrite (t) by uraninite. Uraninite spherules and threads in quartz, but not in siderite (s).

FIG. 11. Selective replacement of quartz (q) and tetrahedrite (t) by uraninite but not of siderite (s).

FIG. 12. Quartzite cut by veinlet of siderite (s) with tetrahedrite (t) and pyrite (p) and minor replacement of quartzite wall. Late uraninite (stippled) preferentially replaces quartzite and vein quartz (q).

achimsthal in Bohemia, for example, rich silver ores in places give way in depth to uranium ores with very marked vertical zoning.[16] Apparently in direct opposition to this view, however, is the evidence that uraninite is one of the late minerals and therefore should be one of the lower-temperature minerals. As such, it would not normally be expected to become more abundant with depth.

SIMILARITIES WITH OTHER PRIMARY URANIUM DEPOSITS.

The uranium-bearing veins of the Silver Belt possess a number of characteristics in common with the primary uranium deposits of Great Bear Lake, Joachimsthal, and Shinkolobwe. Among these are the following:

1) The veins occur in Precambrian sedimentary rocks or their metamorphic equivalents.

2) Cobalt, arsenic, and manganese minerals are commonly associated with the uraninite-bearing veins. Two major uranium deposits (Joachimsthal and Great Bear Lake) have been productive in silver.

3) The principal non-metallic gangue minerals are carbonates and quartz. Hematite and barite are also common.

4) Red staining of gangue minerals or wall rock or both is closely associated with the primary uranium mineral at Great Bear Lake and Joachimsthal.

CONCLUSIONS.

The search for uranium in the Silver Belt was undertaken because the geologic and mineralogic setting appeared favorable. Any deposit characterized by a combination of the characteristics listed above would appear to warrant at least a cursory radiometric investigation, although it is not known which features may be most significant. In the Silver Belt, a characteristic red staining of the wall rock always accompanies significant amounts of uranium, and cobalt, although not always associated with uranium, has proved a useful guide. The fact that uranium is associated with quartz and silicified zones indicates the importance of examining veins which might not otherwise appear to be of commercial importance. Vertical zoning may be important but conflicting evidence makes impossible a definite conclusion at present.

GENERAL EXPLORATION BRANCH, U. S. ATOMIC
ENERGY COMMISSION, SPOKANE, WASH.
AND
GENERAL EXPLORATION BRANCH, U. S. ATOMIC
ENERGY COMMISSION, NEW YORK, N. Y.,
May 14, 1950.

[16] Petrascheck, W., Die Minerallagerstaten des Sudentenlandes: Zeitschr. Berg-, Hütten-, u. Salinenwesen. preuss. Staate, vol. 86, pp. 443–475, Berlin, 1938.

THE GEOLOGY OF THE AGUILAR LEAD–ZINC MINE, ARGENTINA.

FRANK N. SPENCER, JR.

CONTENTS.

	PAGE
Abstract	405
Introduction	406
General geology	408
Sedimentary rocks	410
Igneous rocks	412
Faulting	412
Mine Geology	414
Ore-bearing horizons	416
Faulting and folding	419
Contact metamorphic and pyrometasomatic alteration	422
Silicate mineralization	423
Origin of the tactite	425
Relationship of the tactite to the granite	426
Ore Deposits	426
Mineralization	426
Paragenesis	427
Ore types	427
Factors influencing localization of ore	427
Calcareous and silicated rocks	427
West Branch fault	428
Canedo fault system	428
East dipping shear	428
Folds	429
Distribution of metal values and zoning	429
Genesis of the deposit and its age relationships	430
Age of mountain building	430
Source of ore mineralization	431
Relationship of the deposit to the granite mass	431
Classification of the deposit	432

ABSTRACT.

The Aguilar deposit, in northern Argentina, is a hypothermal lead, zinc, silver replacement in Cambrian calcareous quartzite. The rocks had previously been altered to tactite by a granite stock whose contact is from 150 to 250 m from the ore bodies. The deposit lies between the granite and a post-tactite, pre-mineral fault of some 3,000 m displacement. The fault provided the ore channel and also prepared favorable areas for later ore deposition by shearing the calcareous and tactite rocks. Both bedded and shear-zone deposits are present. The granite and the mineralization are believed to be of late Tertiary age.

INTRODUCTION.

THE Aguilar Mine, situated in the Aguilar range of the Andes in northern Argentina, is at present the leading producer of lead, zinc and silver in that country.

Although the deposit was known to the Incas, and apparently to the early Spanish colonists and the Jesuits stationed at Yavi near La Quiaca, on the present Argentine-Bolivian border, little or no attempt to exploit these ores had been made because of the refractory nature of the unoxidized lead-zinc mineralization. An old charcoal smelter of uncertain date, several kilometers from the present mine, is believed to represent the one and only short-lived attempt by the Conquistadores to recover silver from the deposit. Following the Colonial period, the outcrop lay unnoticed until about the period of the first World War when, due to higher metal prices, renewed interest in lead and zinc attracted prospectors into this, then isolated, district. Development in a small way by local prospectors continued from that period intermittently until 1928 when the deposit came to the attention of its present owners, the Compañía Minera Aguilar, S.A. A development program was initiated by this company, which included both core drilling and underground work, and by 1932 had indicated a substantial tonnage of ore. Low metal prices during the early 30's however, delayed the installation of a plant and concentrator until 1936. Since that year, the mine has produced—depending upon economic conditions—between 150,000 and 280,000 metric tons of crude ore annually.

Location.—The Aguilar district extends for about 10 km along the eastern slopes of the north-south Aguilar range in the Province of Jujuy. The mine is connected by a 50 km paved road to Tres Cruces, a station of the Argentine State Railway between the provincial capital, Jujuy, and La Quiaca, which is some 120 km north of the mine. Aguilar is 1,900 km from Buenos Aires by rail, and 900 from La Paz, Bolivia. The elevation of the mine is 4,450 m (14,600 ft) at the lowest workings and 4,750 m (15,600 ft) at the highest outcrop. The latitude is approximately 23° 15′ South and longitude 65° 42′ West (Fig. 1).

Physical Features.—The Andean region of northern Argentina is a continuation of the Bolivian "altiplano," a plateau area with a general elevation in Argentina of between 3,500 and 4,000 m (11,500 to 13,100 ft). Numerous mountain ranges of north-south orientation, rise 1,000 m or more, above the plateau surface. A few individual peaks are considerably higher. Mount Chani, near Jujuy, rises to 6,200 m (20,300 ft). The highest point in the Aguilar mountains is 5,150 m (16,900 ft). Many of the ranges are block fault type with steep talus slopes and large alluvial fans spreading into the valleys. Others are of gentler topography on anticlinal structures. The only volcanic peaks in the area are along the high mountain chain on the Chilean border which forms the western limit of the altiplano some 150 km west of Aguilar. The eastern margin is between 50 and 70 km to the east of the mine and is formed by a rugged chain of mountains to the east of which are the low plains of the Chaco.

Many of the higher mountain valleys show glacial action. In the Aguilar mountains only the valleys of the central part of the range show cirques and

"U" shaped topography, together with lateral and terminal moraines. It appears that the glaciers did not extend to elevations lower than 4,000 m.

The valleys of the altiplano are generally alluvium filled, from 10 to 30 km wide, with a few minor bed-rock hills rising from their floors. Much of the area west and north of Aguilar has no drainage outlet to the sea. A few

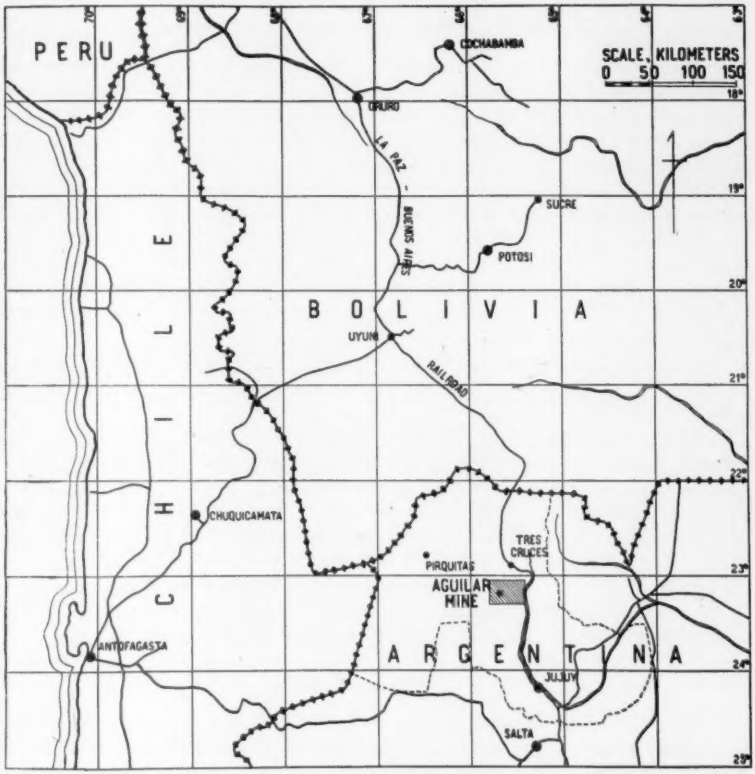

FIG. 1. Regional map of northwest Argentina, Chile and Bolivia, showing the location of the Aguilar district.

fresh water lakes and swamps exist which eventually drain into salt basins or "salares." Some of these are as much as 15 by 75 km in area, and are worked for their sodium chloride, soda and borate content. The Chilean border marks the eastern limit of the Pacific drainage, and the Aguilar mountains the western limit of the Atlantic system in the immediate neighborhood of Aguilar.

Although the semi-desert altiplano lies in the sub-tropics, there are no extremes of temperature. Minimum temperature in the winter seldom falls be-

low 20° F and many days are pleasantly warm. The summer maximum is about 75° F. The only objectionable feature is the high winds which may blow steadily for several days at a time during the winter. The rainy season occurs during the summer months from December to March. Precipitation during the rest of the year is usually limited to a few light snow falls in the higher altitudes. Most streams in the area flow throughout the year and provide ample water for the Aguilar mill.

Even though the altiplano has a heavy summer rainfall, it supports little vegetation because of the altitude and the dry winter climate. The mountain areas above 4,500 m elevation are almost barren. The lower altitudes support several species of coarse grasses, tola brush, similar in appearance to North American sage, a species of resinous moss called yareta, and several species of cacti. The only tree in the area is the queña, which grows to a maximum of about 3 meters. It is found in minor quantities in a few protected valleys, and together with the yareta provides fuel for the local Indians.

Previous Geological Work.—As the Aguilar deposit was relatively unknown prior to 1930, few of the earlier geologists who carried out extensive investigations in Bolivia visited the property, and no technical information was published until John S. Brown's paper (4) [1] appeared in 1941. Further notes appeared in his book, Ore Genesis (5), published in 1948.

Pascual Sgrosso, geologist for the Argentine Dirección de Minas y Geología, described the deposit in a bulletin (13) of that organization, in Spanish, in 1943.

Acknowledgments.—The author's greatest indebtedness is to John S. Brown, much of whose early work on the district and mine geology, and particularly his microscopic work on the mineralogy and paragenesis, which is not acknowledged directly in the references, has been used in this paper. His later advice and criticism have been invaluable. The author wishes to thank Dr. Paul F. Kerr of Columbia University, and Dr. A. F. Buddington of Princeton University for their reviewals and criticisms of the paper.

The author also expresses his appreciation to the management of the Compañía Minera Aguilar for their permission to publish this paper.

GENERAL GEOLOGY.

The rocks of the Aguilar district and surrounding area range from Precambrian through Paleozoic and Mesozoic formations to late Tertiary and Pleistocene. In a regional picture the various periods have not been correlated accurately because of the small number of fossils found, and because of the reconnaissance nature of the regional geological mapping done so far. A number of igneous rocks occur, including intrusions of granite, granodiorite and syenite, and extrusions of dacite and other lavas. Most of the igneous rocks are believed to be Tertiary or later, but Sgrosso (13) and Groeber (7) classify some of the granites as probably Permo-Triassic.

Mountain building of the Andes is chiefly in the form of sharp anticlinal structures with north-south axes which form the present ranges of the alti-

[1] Numbers in parentheses refer to the Bibliography at the end of the paper.

plano. Commonly the anticlines are flanked by normal block faults of large displacement.

In the Aguilar range and the immediate neighborhood of the mine, the lowest formation exposed is the Aguilar quartzite, believed to be Cambrian. The formation outcrops throughout the Aguilar range in the form of an anticline, or dome. Near the central part of the range, which is about 35 km in length, two exposures of granite outcrop, one on each flank of the mountains,

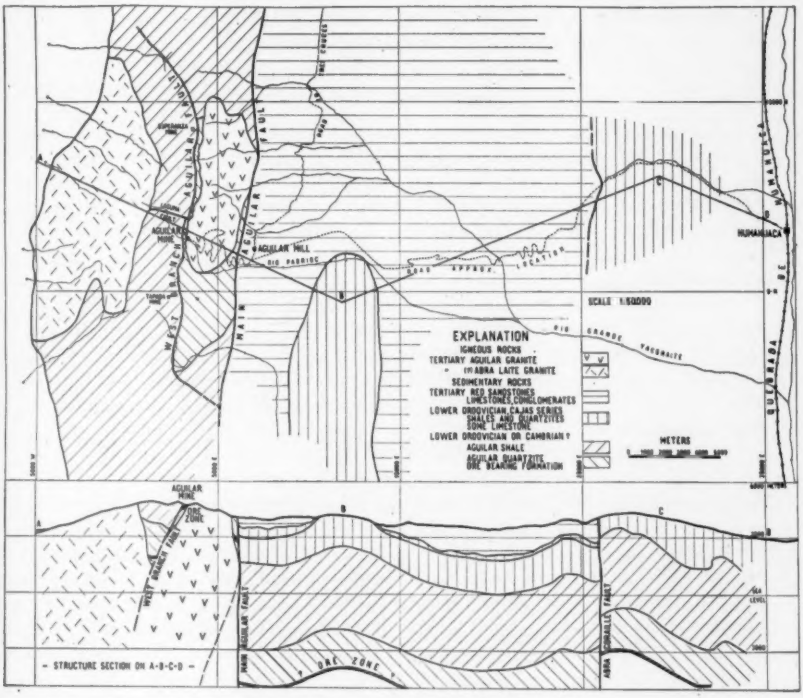

FIG. 2. Geological map and section of the Aguilar district (after J. S. Brown).

the Aguilar on the east and the Abra Laite on the west (Fig. 2). The former gave rise to the contact and pyrometasomatic alteration in calcareous beds of the quartzite, with which the deposit is associated.

The basal quartzite is overlain by the Aguilar shale, a thick series of shales with some interbedded quartzite and conglomerate. Above the shale is the Cajas formation containing lower Ordovician trilobites (9), overlying which are the Mesozoic and Tertiary beds. It appears that all these formations, with the exception of the recent unconsolidated deposits, are folded more or less in the same degree and manner, and that the unconformity between the Paleo-

zoic and Mesozoic formations must have been roughly parallel to the stratification.

The eastern border of the anticline is marked by a block fault downthrown to the east which brings the Aguilar quartzite in contact with the Tertiary. The thicknesses of the formations involved show that the displacement is at least 5,500 m (18,000 ft). It is known as the Main Aguilar Fault (Fig. 2). A branch from this fault, called the West Branch, forks off in the southern part of the range, and cuts northward through its center slightly west of the anticlinal axis and the Aguilar granite. It is downthrown to the west, with a displacement calculated at 3,000 m maximum (10,000 ft).

Sedimentary Rocks.

Aguilar Quartzite.—The lowest exposures of the Aguilar quartzite are the ore-bearing beds of the mine, which are the only calcareous rocks known in the section. These impure limestones, mineralized in part, are some 400 m (1300 ft) thick including interbedded shale which comprises about half the ore-bearing section. The beds are exposed in a narrow band of the formation between the Aguilar granite on the east, and the West Branch of the Aguilar Fault on the west.

The remainder of the formation above the ore zone takes the form of a dome roughly surrounding the Aguilar granite. The formation consists of a series of quartzite beds with lesser interbedded shales. The individual quartzite bands range from about a meter to ten meters in thickness and are largely massive with little indication of the stratification. However, the bedding is easily apparent in the broader picture, because of differential erosion of the quartzite and the softer interbedded shale.

The surface of the quartzite ranges from dirty gray to brownish and reddish tones. The color may extend along numerous fracture planes below the surface. In places manganese dendrites are found on the fractures, but it is obvious that the manganese and iron content, which doubtlessly produced the coloration, is minor. On freshly broken surfaces the quartzite is white. Individual quartz grains are not normally visible megascopically, and are probably less than 0.5 mm. Under the microscope (13) calcareous cement is sometimes evident, as well as minor quantities of accessory zircon, rutile and biotite.

The exposed section of the formation is estimated to be 2,000 m thick (6,500 ft). Its contact with Aguilar shale, which overlies it, is rather gradational.

Aguilar Shale.—These shales outcrop over most of the range, west of the West Branch fault, and form the hanging wall of the ore zone at the Aguilar mine. In the central part of the range between the Abra Laite and Aguilar granites, the shale has been altered to a dense hornfels. As the distance from the intrusives increases, the hornfels grades into slate, and finally at the northern and southern extremities of the range, into normal shale. The lower part of the formation contains a few bands of conglomerate, quartzite, and calcareous rocks. Many of these bands are discontinuous, but two have sufficient continuity so that the folded and contorted structure of the formation could be de-

termined with enough accuracy to estimate its thickness, and also the displacement of the West Branch fault. A total thickness of 4,000 m (13,000 ft) can be measured.

The prevailing color of the formation is dark to black on both weathered and fresh surfaces. In the un-metamorphosed parts it is a normal, soft, fine grained shale weathering to platy fragments. The hornfels, on the other hand, is a hard, massive, siliceous rock with few signs of the original stratification.

The formation contains a number of minor mineral showings, chiefly in calcareous strata close to the West Branch fault. The Esperanza deposit, which shows galena-sphalerite mineralization in a barite gangue, replaces a band of calcareous quartzite about 2.5 m thick (Fig. 2). It is the only deposit of any importance other than the Aguilar mine.

The contact of the Aguilar shale with the overlying Cajas formation has not been found, and the latter has been entirely eroded off in the Aguilar range.

Cajas Formation.—The Cajas formation is exposed in an anticlinal structure (Fig. 2) in the broad valley east of the Aguilar fault, and also in the mountain range forming the eastern flank of the valley 25 km east of Aguilar. Like the first two formations described, it contains a basal quartzite and overlying shales. Although the quartzite section is somewhat similar to the Aguilar quartzite, the shales are quite different from the Aguilar shale.

In the transition zone between the two parts of the formation, a number of thin strata of phosphatic limestone occur which contain numerous trilobites and a few brachiopods. Nine species of trilobites were identified by Kobayashi (9) who places them in the lower Ordovician.

The complete section of the formation has not been studied. Some shales interstratified with the lower quartzite are green colored. Thinly laminated, black carbonaceous shales overlie the transition limestones and are cut by an unconformity several hundred meters higher. The total known thickness of the formation is 2,000 m (6,500 ft).

The actual contact of the Cajas unconformity with the overlying rocks is not clearly exposed, but field relationships leave little doubt of its approximate location.

Mesozoic and Tertiary Formations.—The Mesozoic and Tertiary rocks, corresponding to the petroleum-bearing formations of the lowlands of northwest Argentina and eastern Bolivia, are widespread on the altiplano. Near the mine they are well exposed in the broad valley just east of the Aguilar range. Numerous unclassified Tertiary fossils have been found in limestones in the central part of the section.

The lowest exposed member, a red sandstone with a basal conglomerate, is believed to be Cretaceous, but no clear unconformity with the Tertiary is exposed.

Tertiary rocks consist chiefly of red sandstones and conglomerates with lesser thickness of limestones and shales, and overlie the basal formation. The highest known member is a coarse conglomerate about 1,000 m (3,300 ft) thick. Most of the conglomerate is derived from the lower parts of the Tertiary, and fossiliferous limestone boulders from the middle Tertiary have been

found. It also contains numerous granite boulders, showing that some granite existed in the area prior to the mountain building, but it is noteworthy that the boulders show no resemblance to either the Aguilar or the Abra Laite granites.

The total thickness of all these rocks is estimated at about 3,000 m (10,000 ft).

The formations contain no known mineral deposits, but possibly contain petroleum, evidenced by a small oil seep about 20 km north of Aguilar.

Alluvial Deposits.—Recent alluvium is extensive in the valleys, both water and glacier-laid. It ranges from finely laminated clays and gravel stream wash, to coarse glacial detritus along the lower slopes of the mountains. Much of the glacial material has been re-washed by mountain streams into large alluvial fans.

Igneous Rocks.

Aguilar Granite.—As already explained, this granite is located in the dome-shaped structure of the Aguilar quartzite in the form of an elongated stock along the east flank of the range. Its outcrop is about 9 km long and 2 or 3 in width. The Aguilar and West Branch faults cut the sediments bordering the granite a short distance from the contacts on the flanks of the dome.

The granite varies from gray to reddish on its surface exposures. The fresh surface is grayish. It is generally of medium grain, containing about 35 percent of quartz, and the remainder chiefly orthoclase with some oligoclase. A small percentage of biotite and a little zircon are present as accessory minerals. A minor amount of fluorite is present, particularly in the dikes exposed in the mine workings. The fluorite content of the main granite mass has not been investigated thoroughly.

Abra Laite Granite.—This stock takes an analogous position to that of the Aguilar on the west flank of the range. The exposure is considerably larger and more irregular in shape. On the west it is covered by valley alluvium and there is no certainty that a regional block fault exists on the west of the range. Granite outcrops known to occur in the mountains some 20 km farther west, suggest the existence of an underlying batholith of considerable extent with an east-west orientation.

The appearance and character of the Abra Laite granite are similar to the Aguilar, except that it contains less plagioclase and no known fluorite, and that there is strong development of a porphyritic texture along its contacts. A few mineral deposits of a minor character appear to be associated with this granite.

Faulting.

The large block faults on the flanks of the regional folding are the important ones in the general structure. In addition, a number of minor north-south faults associated with the movement of the West Branch have been exposed in the mine workings and complicate the local structure of the ore bodies. A few later east-west faults have cut and displaced the others in the mine area.

Main Aguilar Fault.—The main Aguilar fault is well exposed in a number of localities just east of the Aguilar range. Where it is not exposed, its effects can be traced for at least 25 km along the mountain front, and it may extend considerably farther.

The actual exposures are several meters in width, consisting of crumpled shale and gouge. Its eastward dip, together with the fact that it brings the Tertiary on the east side of the fault in contact with the Aguilar quartzite and shale on the west, demonstrate its normal action.

In the clearest exposures the upper horizons of the Tertiary are in contact with the Aguilar shale, and therefore its minimum displacement can be calculated as including the full thickness of the Tertiary, 3,000 m the Cajas, 1,500 m, and about 1,000 m of the Aguilar shale, a total of 5,500 m (18,000 ft). The existence of the Aguilar quartzite near the fault at some points indicates that the displacement may be considerably more. In general the Paleozoics are highly contorted near the fault, and the Tertiary in its hanging wall usually is standing almost parallel to its plane.

Abra Coraille Fault.—The Abra Coraille fault occurs on the Western front of an anticlinal mountain range bearing the same name some 25 km east of the mine. It is downthrown to the west, and in other respects is similar to the Aguilar fault in action as well as displacement. It brings the upper Tertiary in contact with the Cajas series.

West Branch of the Aguilar Fault.—As previously mentioned, the West Branch fault cuts off the westward dipping Aguilar quartzite with its ore-bearing zone at the mine and brings the quartzite in contact with the overlying Aguilar shale. Detailed study of the shale formation by Brown showed that the maximum displacement occurred in the neighborhood of the Aguilar deposit, where 3,000 m (10,000 ft) could be accounted for, including the upper part of the quartzite and the lower part of the shale. It therefore faults the ore-bearing beds to depths beyond mining range. This important question has been checked in recent years by core drilling west of the fault to a depth of 750 m (2,300 ft). The hole showed no signs of the Aguilar quartzite, tending to confirm the original estimate on displacement.

The character of the exposures underground are surprisingly ill-defined for a fault of such large displacement, and the fault went unrecognized in the early exploration period. Development later showed that the beddings were clearly cut off, and exposed the fault at sufficient points so that its character could be recognized. The strike is generally north-south and the dip from 50° to 60° west. Where there is no disturbance by later faulting, it consists of a zone of shearing from 5 to 10 m wide (16 to 33 ft) with minor amounts of gouge. On the surface little can be seen of the fault itself, but its effects clearly bring the west-dipping quartzite in contact with the contorted hornfels in the hanging wall.

The evidence indicates that the rupture occurred after the contact and pyrometasomatic alteration in the ore-bearing calcareous rocks, but before the granite reached its final position, and is therefore pre-ore. In areas where both walls are shale, the degree of alteration to hornfels is much the same on

the two sides, which is the main reason for its obscure appearance. The fault itself does not seem to be affected by the alteration.

In its northward extension the displacement decreases rapidly, and the fault dies out within ten kilometers of the mine. To the south it swings to the southeast to join the main Aguilar fault.

Canedo Fault System.—The faults of the Canedo system are known only within the mine workings. They are of minor importance in the regional geology, but are highly important in the local geology of the ore bodies. All are downthrown to the west, and are connected with the action of the West Branch fault. They will be discussed more fully under "Mine Geology."

Laguna Fault.—The Laguna fault is one of the few east-west faults known in the area, and is exposed a few hundred meters north of the mine workings. The dip is north and its normal action has displaced the outcrops of the West Branch fault and the Aguilar quartzite about 200 m to the east. The fault does not extend into the granite on the east, and evidently occurred before the granite had solidified.

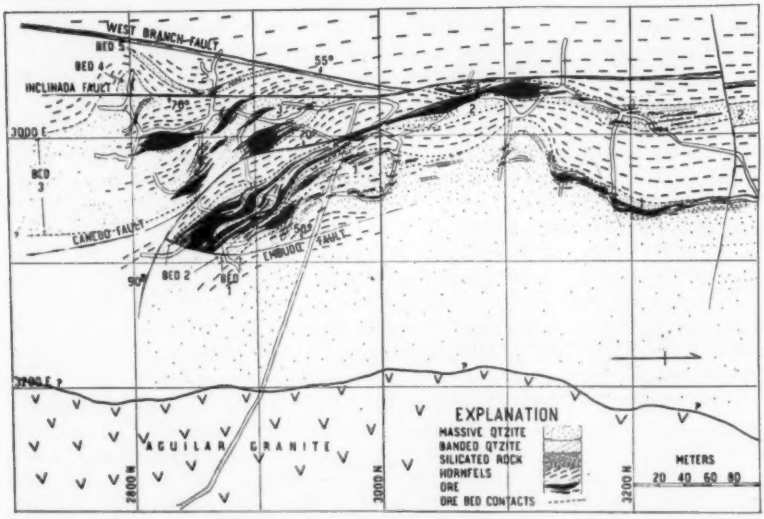

FIG. 3. Geological map of Canedo level, south, Aguilar mine.

MINE GEOLOGY.

The West Branch of the Aguilar fault is unquestionably the controlling structure of the deposit, as well as a number of minor deposits, all of replacement type, scattered along the eastern front of the range. The ore bodies at the mine all occur in a block of Aguilar quartzite extending some 1,500 m (4,900 ft) along the footwall of the fault with a width of from 200 to 300 m (650 to 1,000 ft) between the fault on its west and the granite on its east.

The ore-bearing block is limited on the north by the Laguna fault, and a subsidiary plane known as the Number 8 fault. On the south its surface exposure is cut off by a westward protuberance of the granite which almost reaches the West Branch fault.

The rocks within the block are a series of quartzites, arkoses, calcareous quartzites grading into purer limestones, and interbedded shales. All of these rocks show the effects of contact metamorphic alteration. In the mine area the West Branch fault has a strike of north 12° east and dips from 50° to 60° west. The ore-bearing formations are much contorted but have a general strike of from south 10 to south 30° east, and dip from 40° to 45° west. They are therefore cut off by the fault in depth as well as in their northward extensions, and their intersections with the fault rake south at a low angle.

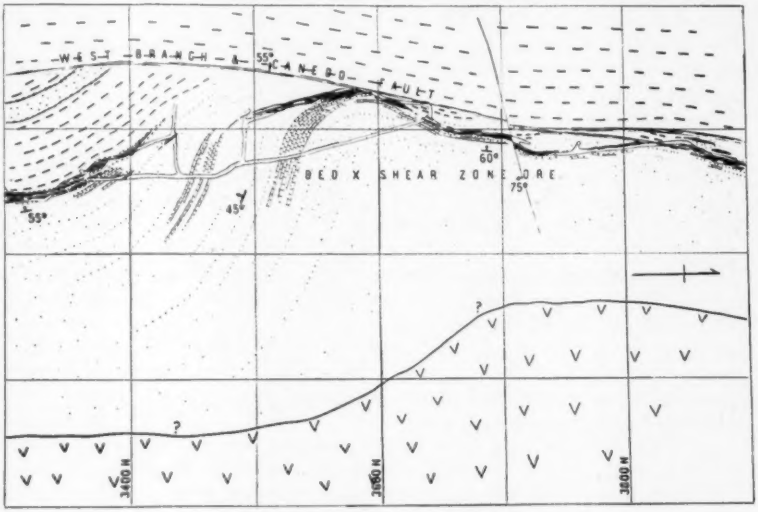

FIG. 4. Geological map of Canedo level, north, Aguilar mine.

Because of the complicated folding the stratigraphic thickness cannot be measured accurately, but is believed to be on the order of 400 m (1,300 ft). The lower 200 m are known as the Footwall quartzite. Above this are six distinct strata of calcareous quartzites with interbedded hornfels members. With the exception of the hornfels, all the members are ore-bearing in varying degrees. The Footwall quartzite is also known as Bed X, and the other calcareous beds are numbered from 1 to 6, with Bed No. 1 in the immediate hanging wall of Bed X. Of these, only Beds X through No. 4 contain important quantities of ore.

Alteration of the original sandstones to quartzites is a regional effect and has no relationship to the granite. On the other hand, the alteration of the shale to hornfels is clearly related to the granite, as it dies out into normal shale

within a few kilometers of the granite contact. The calcareous rocks in the mine workings all show strong alteration to the silicate minerals, and little of the original limestone can be seen.

Two general types of ore bodies occur: replacement along the calcareous stratigraphic horizons, and replacement along a shear zone in the footwall of the West Branch fault. The former type is found in the southern part of the mine where Beds No. 1 through 4 swing away from the West Branch fault toward the south-east. The latter type is confined to the northern part of the mine along the truncation of the Footwall quartzite by the West Branch fault. The two types are gradational, as the shearing action of the fault has much to do with the localization of both (Figs. 3, 4 and 9).

Although the geological picture of the deposit as a whole appears to be rather simple, many of the local details are quite complex, and the identification of the various beddings has been in doubt in a great many cases. Faulting, sharp local folds, sudden thickening and thinning of the beds, and the fact that the quartzites as well as the shale members are very similar in character, all tend to obscure the local geology.

Ore-Bearing Horizons.

Bed X.—The strata of Bed X are the lowest known exposures of the Aguilar quartzite formation. They are highly compressed and somewhat folded, and consist of a number of bands of white to gray quartzite, strongly silicated calcareous quartzite, and hornfels. Quartzite predominates, with the tactite of secondary importance. In most areas the shales have been eliminated by squeezing. Many parts of the strata show sedimentary banding. The individual bands are from one to four centimeters thick and vary from white and gray to yellow and brown. Some of these are calcareous and commonly contain galena and sphalerite. In the limey rocks irregular banding and bunching of the silicate minerals is common, but the bands normally bear little relationship to the rock strata.

Bed No. 1.—Bed No. 1 constitutes the hanging wall zone of Bed X, and is from 2 to 10 m thick (7 to 33 ft). The original bed was distinctly calcareous with some almost pure limestone which was later altered to coarse calcite in grains from 0.2 to 0.3 mm in diameter. The calcareous rock normally forms the central part of the horizon and is bordered by more siliceous rocks carrying quartz grains in a calcareous cement. These latter parts are mostly strongly altered to the silicate minerals, chiefly diopside, wollastonite and rhodonite with minor amounts of garnet. Galena and sphalerite occur irregularly, and numerous almost barren areas exist in the horizon.

This bed is one of the few distinct marker horizons in the mine, but in localities where it is pressed against Bed No. 2, its position may be in doubt.

Bed No. 2.—Beds 1 and 2 are normally separated by a hornfels horizon which varies in thickness from zero to 50 m. Bed 2 is from 20 to 40 m thick. In some areas the formation consists of three bands of quartzite and calcareous quartzite with intervening hornfels, but much of it is compressed and shows no hornfels whatsoever. The siliceous parts, which again predominate toward the two walls, are similar to those of Bed No. 1 and contained a cal-

careous cement which gave rise to the silication. The ore mineralization is strong, but irregular. In some sections ore extends over the full width of the horizon and in others the bed is almost barren.

Bed No. 3.—Hornfels of uncertain thickness, and also a strike fault known as the Canedo, separate Beds 2 and 3 (Figs. 5 and 6). In the developed part of the mine there are no exposures of Bed 2 west of the fault, and none of Bed 3 to the east. Therefore the displacement of the fault and the thickness of the intervening hornfels have not been detrmined. The thickness of Bed 3 is from 45 to 65 meters. Sharp local folds exist, but in general it is rather regu-

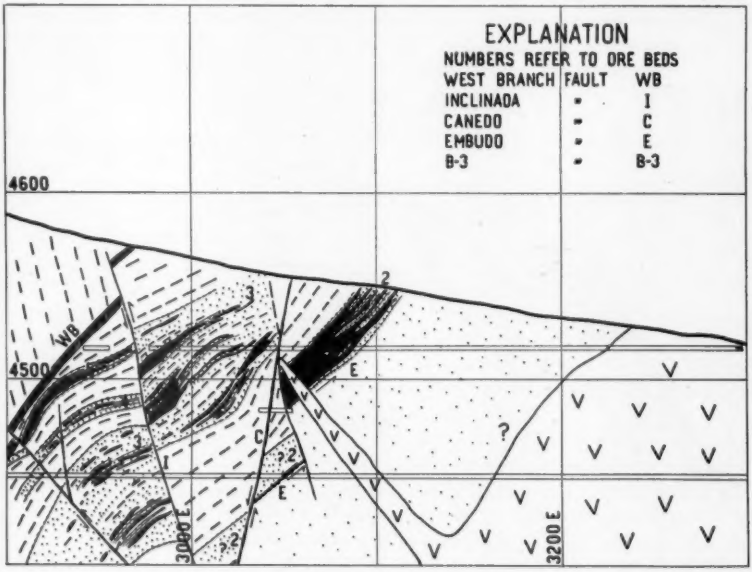

FIG. 5. Cross section at coordinate 2,855 north, looking north, Aguilar mine.

lar. The lithology, however, is very irregular. The bed contains about 30 percent or 40 percent of shale interstratified with 5 or 6 bands of quartzite and calcareous quartzite similar to those of Bed 2. Many of these bands are broken into lenses of various sizes, the smallest of which may be measured in a few tens of meters in their longest dimension. Again the purer quartzites are near the walls, and the more calcareous rocks toward the center of the bed. Silication appears to be slightly weaker, and ore mineralization more irregular both in respect to the lenticular nature of the favorable rocks, and distribution of ore within the lenses.

Bed No. 4.—This bed is separated from Bed 3 by 20 to 40 m of hornfels. Thickness is from 6 to 12 meters. The bed has a more calcareous nature than any of the others, with the possible exception of Bed 1. It parallels the West

Branch fault for about 150 m and is cut off by the fault at its north end, as are the other beddings. Ore is continuous in the 150-meter section, but fades to the south where the bed swings away from the fault toward the south-east. Banded structure of a shaly nature is common, and silicate alteration is less noticeable.

Other Beddings.—Bed 5 lies 10 or 15 m in the hanging wall of Bed 4. It is a few meters thick, consisting of calcareous quartzite and contains ore only near its intersection with the West Branch fault. In the southern extension of the bed, the mineralization is very weak in broken fragments of the horizon.

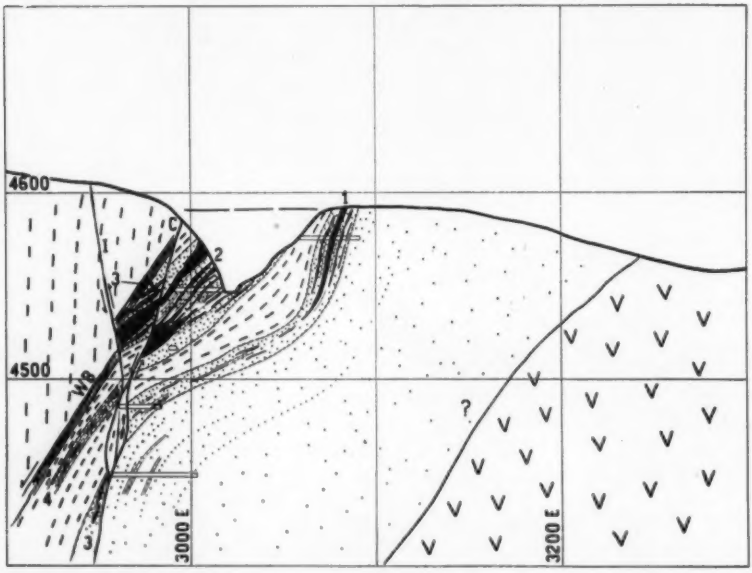

FIG. 6. Cross section at coordinate 3,025 north, looking north, Aguilar mine.

Bed 6 is a similar quartzitic horizon carrying traces of galena and sphalerite exposed on the surface. Its correlation with the other ore-bearing horizons is not certain.

Interbedded Hornfels Members.—All of the shales, or hornfels, including the Aguilar shale of the hanging wall, are similar in character. They are black, fine-grained rocks, considerably foliated from the pressure which thinned and thickened them at many points. Occasionally banding is noticeable, in places due to schistosity.

The hornfels alteration is characterized megascopically by the hard, silicified appearance of the rock, and also typical spotting of feldspar knots 1 to 2 mm in diameter. The microscope shows that the knots are frequently altered to sericite. Many sections show biotite and pyrrhotite. The local limey

character is indicated by the presence of garnet, calcite and actinolite. The microscope does not show any appreciable difference between the various beds.

The Aguilar shale west of the West Branch fault shows some slight differences from the interbedded members, but these are by no means sufficient to permit positive identification in the great majority of cases. It is usually fractured into blocks of 4 or 5 cm, and the joints show a greenish chlorite coloration. This is sometimes apparent in the other hornfels, but the development is not so pronounced. Bands of dense quartzite from 0.5 to 2 m thick are also found locally. Although such bands exist in the other members, they usually show a slight development of the silicate minerals. No silicates are found in the purer quartzites of the Aguilar shale.

Faulting and Folding.

So far as is known, all the important north-south striking faults in the mine are downthrown on their west walls.

The rocks have been contorted and shattered to such a degree that only two systems of jointing have sufficient regularity to be mapped. One of these systems is parallel to the West Branch fault, and the other dips east at 45 degrees with a north-south strike.

The Canedo system of north-south faulting was the earliest movement following the folding, and was prior to the West Branch fault, the silicate alteration, and the ore mineralization. The earliest of these faults, the Embudo (Figs. 3, 5) shows definite movement prior to the granite dike stage. The inference is that the Canedo faults represent the borders of blocks dragged upward on the east by the intruding granite.

The West Branch fault was the second important movement in the mine area, and occurred after the silicate alteration, but prior to the ore. Briefly, there is evidence that the fault shattered the silicates, producing favorable localities for ore deposition. These features will be discussed under the section dealing with ore localization. The relationship of the fault with the ore bodies, and the fact that traces of similar mineralization exist west of the fault, give rather positive evidence that it is pre-mineral.

Following the West Branch, a number of movements of reverse faulting took place. These are the east-dipping B-3 fault which displaces the West Branch, and a vague shearing, parallel to the B-3, which was mentioned above. The shearing is post-silicate, and pre-ore. The two were probably contemporaneous and are downthrown to the west. The Laguna and No. 8 faults occurred at about the same time. The final movements, of post-ore age, were a reopening of the faults of the Canedo system. The age is shown by crushed ore along them as well as the fact that the ore beddings were displaced considerably more than the West Branch fault where it is cut by the Inclinada, a fault of the Canedo system (Fig. 5). The size and appearance of all the faults seem to bear little relationship to their displacements. The Canedo fault with a probable displacement of less than 100 m commonly has the aspect of a stronger movement than the West Branch whose displacement is measured

in thousands of meters. The fact that the faults of the Canedo system were reopened after ore deposition suggests that these later movements took place after considerable erosion had occurred, and therefore under much lighter load than the pre-ore movements, resulting in a looser brecciation as compared to the tight shearing of the deeper seated faults.

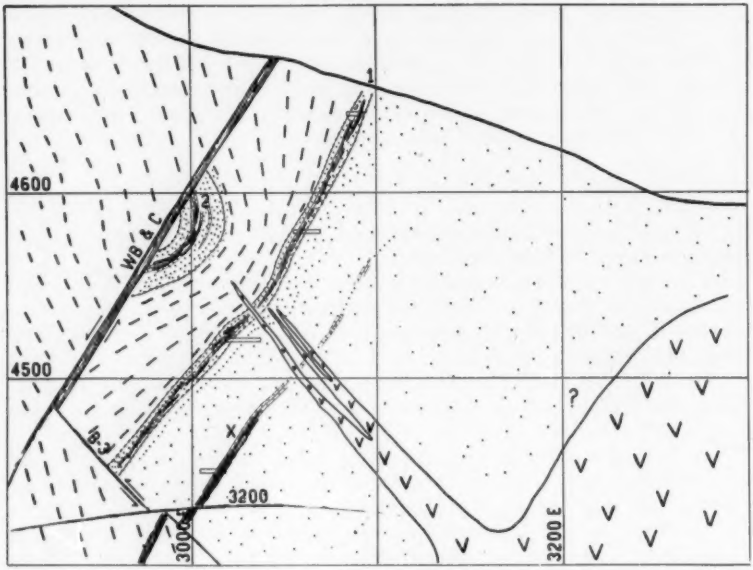

FIG. 7. Cross section at coordinate 3,400 north, looking north, Aguilar mine.

Embudo Fault.—The Embudo is the earliest fault of the Canedo system, and occurred prior to the granite dike stage as shown in Figure 5. Weak shearing within the granite on the line of the fault shows that there was slight post-granite movement, but no displacement can be measured. The fault is cut off by the Canedo. As the displacements of both the Embudo and Canedo are not known, the downfaulted position shown for Bed 2 in Figure 5 is hypothetical, as it has not yet been found in actual development. Considerable horizontal component in its displacement is indicated by a gap in the faulted position of Bed 2, and also by strong mullion marks raking down the dip at a low angle. The fault is generally from 20 to 40 cm wide with a gouge filling.

Canedo Fault.—The displacement of the Canedo fault is known only as a minimum of about 75 m (250 ft) vertically. It varies from 50 cm to 2 m in width with a filling of gouge and brecciated material. It dips steeply to the west as shown in Figures 5 and 6, and joins the Inclinada fault in depth. The Canedo controls the movement, and the combination dips westward below the juncture.

Inclinada Fault.—The measured displacement of Bed 3 by the Inclinada fault is 60 to 90 m (200 to 300 ft) vertically, with the lesser movement toward the south end of the mine. The post-mineral movement is also accurately measurable as about 25 m (80 ft), its displacement of the West Branch fault (Fig. 6). The direction of movement is believed to be vertical, although this is not certain. Its appearance is much the same as the Canedo fault.

B-3 Fault.—Although the West Branch has not been found in the footwall of the B-3 fault, the rocks encountered on the footwall side are unquestion-

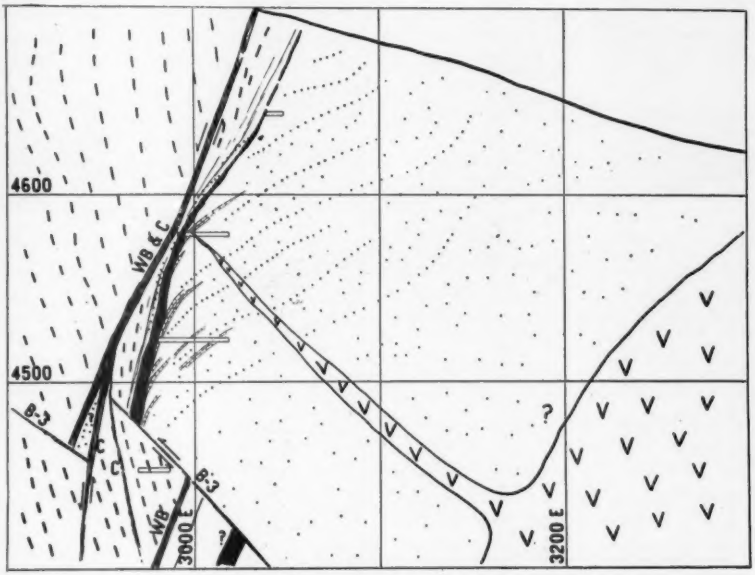

FIG. 8. Cross section at coordinate 3,550 north, looking north, Aguilar mine.

ably Aguilar shale (Fig. 7), showing the fault is reverse action. Thus the West Branch and the ore zone have been faulted to a position below the lowest workings of the mine. As no exploration has been done, its displacement and the continuation of the ore are not known. Extension of the B-3 into the southern part of the mine is uncertain and it has been shown only in the sections covering the north end. The exposures are somewhat weaker than the Canedo and Inclinada faults.

Number 8 Fault.—The Number 8 fault is a subsidiary plane of the Laguna and cuts off the ore bodies at the north end of the mine (Fig. 10), and is similar in size and appearance to the B-3. Its normal action has faulted the West Branch and the ore zone downward and to the east on its north side. Shearing believed to be the post-mineral action of the Canedo continues across the fault on the north projection of the West Branch.

Folding.—Folding of the strata does not seem to be connected in any way with the faulting, and probably occurred previous to all other structural features. A few minor examples of drag folds have been observed along the walls of some faults, indicating the directions of their movements. These are all superimposed on the earlier folds of larger dimensions.

CONTACT METAMORPHIC AND PYROMETASOMATIC ALTERATION.

The development of the silicate minerals in the calcareous quartzites and arkoses is the only important form of alteration so far recognized. Because of the recent glacial erosion, little or no surface oxidation is present in the mineralized outcrops. Some forms of hydrothermal alteration are apparent, chiefly

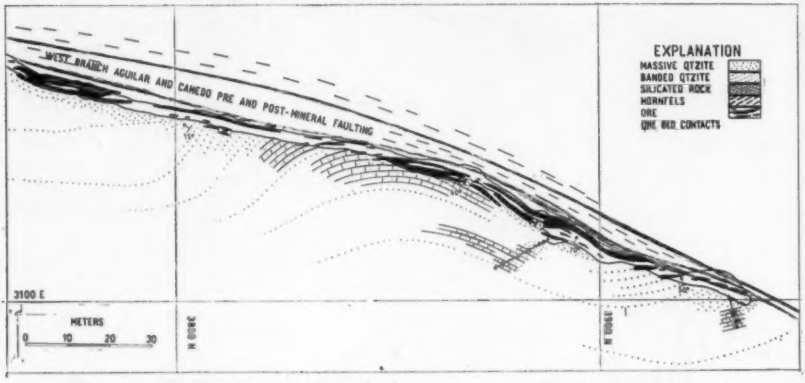

FIG. 9. Detail of portion of Bed X shear zone. North end of X level, Aguilar mine.

that of the silicates to chlorite and sericite. This alteration has not been studied in detail, and its importance to the economic geology of the deposit is obscure.

The hornfels alteration, which includes a large area of the Aguilar shale between the two granites, takes the form of sintering and recrystallization of the silica, and the formation of feldspars. There is no evidence that silica has been introduced. Other minerals such as garnet, amphibole and pyroxene are found occasionally in thin sections, and were also probably developed from the original constituents of the shale by contact metamorphism rather than by pyrometasomatism.

The development of tactite in the calcareous quartzites and arkoses is probably due to both pyrometasomatism and contact metamorphism, as some of the minor constituents of the silicate minerals have doubtlessly been introduced. The tactite alteration is generally irregular. Contortion of the strata, and variations in the original character of the rocks have influenced continuity of the alteration. There is also evidence that the silicate minerals have mi-

grated in many cases. Occasional pure silicate bands a few centimeters in width occur locally parallel to the stratification, evidently the alteration of calcareous bands in the original sediment.

The age of the tactite has been shown by Brown's microscopic work to pre-date the ore mineralization. Replacement of the silicates by galena and sphalerite is common, but the reverse situation has never been noted.

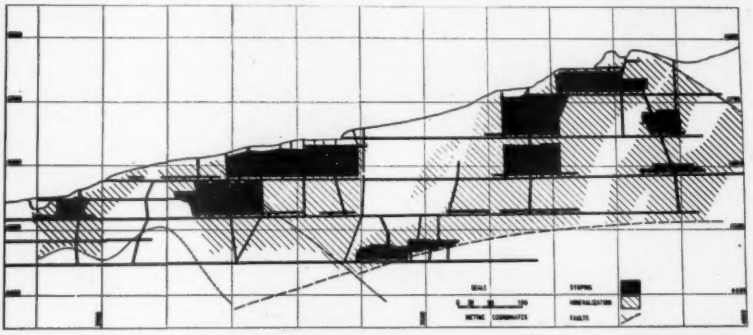

FIG. 10. Longitudinal section of Bed No. 1 (from coordinates 2,900 to 3,400 north) and Bed X shear zone (coordinates 3,400 to 4,000 north), looking west, Aguilar mine.

Silicate Mineralization.

Four gradational types of rock are believed to have been present before the alteration; these are limestone with minor original silica, calcareous quartzite with from 25 to 50 percent silica, a similar calcareous arkose containing feldspar, and the purer quartzite. Although such types may be found in any of the ore beddings, their stratigraphy is obscure because of contortion and alteration. Occasional definite contacts between the types are seen in thin sections. All of the types show differences in the silicate alteration both quantitatively and qualitatively.

What is believed to have been limestone generally contains about 35 percent calcite, 20 percent diopside, 12 percent wollastonite, 6 percent rhodonite and 3 percent garnet. The remaining 24 percent is composed of minor accessories, some alteration products, and the sulphides. Quartz is not present except in an introduced form. This gives a calculated analysis of the rock as follows:

CaO	33.0%
SiO_2	22.1
CO_2	15.2
MgO	3.5
MnO	1.4
Al_2O_3	0.7
FeO	0.02
Other	24.08
Total	100.00

With the assumption that some part of the remaining 24 percent was calcite which has been replaced by the sulphides, the only constituent which must have been introduced was manganese. The magnesia could have originated from previous dolomitization, and the iron and alumina could well have been original impurities in the rock. Thus, the analysis shows a composition of an impure limestone.

The more siliceous limestones and limey quartzites contain sedimentary quartz, in places a little calcite, and more diopside than the purer limestone. Roughly the percentages are diopside 30, quartz 15, rhodonite 10, garnet 8, calcite 5, amphibole 3, and no wollastonite, with the balance of the constituents similar to that of limestone. Calculated analysis is as follows:

SiO_2	41.5%
CaO	16.0
MgO	6.5
MnO	2.6
CO_2	2.2
Al_2O_3	1.8
FeO	0.4
Other	29.0
Total	100.0

Again it appears that all of the silica and lime were available in the original rock for the formation of the silicates. The only possible exception is the manganese.

In the calcareous arkoses the quartz content is about 50 percent and the original feldspars 15 percent. Small amounts of calcite may be present, and lesser percentages of the silicates in about the same proportions as in the siliceous limestones. The purer quartzites contain about 65 percent quartz and up to 20 percent feldspars.

The accessories include minor quantities of augite, titanite, epidote, apatite and zoisite, all probably pyrometasomatic with the exception of augite. The titanium could have been a minor sedimentary constituent, but fluorine for the apatite doubtlessly originated from the fluorite content of the granite. Small amounts of fluorite are found in the sediments bordering the granite dikes. An uncertain fine grained mineral believed to be topaz has been noted in thin sections, as well as tourmaline. A minor occurrence of molybdenite has been uncovered in the wall of one ore body. Its local nature and normal association with the silicates suggest that it was introduced during the alteration period. The scarcity of the iron-bearing silicates is notable at Aguilar.

In general, the grain size of the silicate minerals ranges from 0.01 to 0.2 mm, although in some areas individual crystals up to several centimeters in diameter can be seen megascopically.

In making the above analyses of the limestone and siliceous limestone, two difficulties exist which may have considerable influence on their accuracy. One is the fact that so little completely unaltered rock exists in the mine workings, the real composition of the original sediments cannot be determined accurately. The second is that the number of thin sections used in the compilation, fifty-three, is not sufficient to be truly representative of the deposit. Al-

though the proportions between the quantities of the various silicate minerals in a given rock type may be more or less correct, the error in the total percentage of silicates may be considerably greater. Thus, the totals of 41 percent silicates in the limestone, and 56 percent in the siliceous limestone probably cannot be compared on a quantitative basis.

What is called rhodonite at Aguilar is believed by Brown to be an isomorphous recrystallization of rhodonite and wollastonite with a composition, SiO_2 46.76%, MnO 25.65%, CaO 20.67%, FeO 4.53%, ZnS 2.40%. The sphalerite is an impurity visible in the sample. Although this substance or mineral is similar to pure rhodonite, its optical properties are quite different.

Origin of the Tactite.

From the above it follows that the tactite at Aguilar has been formed by heat and pressure effects from the granite to a much greater extent than by additions of mineral constituents, and consequently can be classed as contact metamorphic rather than pyrometasomatic, although a minor amount of pyrometasomatism is probable. The presence of fluorine, and possibly other volatiles, which emanated from the granite, has probably aided the alteration and helped the silicates to crystallize.

The irregular nature of the silicate occurrences, which in many cases appear to be intruded into the rocks, is strong evidence for an interstitial fluidity in which there was at least slight migration of the minerals. A second indication of migration is occasional examples of silicate knots in quartzite relatively free of lime. These knots vary from 10 to 30 cm in diameter and have an inner core of coarse calcite sometimes replaced by a few spots of galena, and an outer shell of tactite generally containing diopside, and lesser quantities of garnet and wollastonite. Although their origin has not been proved, the explanation may be that a calcareous cement in the quartzite migrated under a fluid condition due to pressure, coalesced into knots, and formed silicates along the quartz-calcite contact.

There appears to be little information in the literature regarding the temperature of formation of contact alteration. Brown (5, p. 104) gives the melting points for some of the tactite minerals as between 1,185° C for molybdenite and 1,825° C for rutile. Obviously, in a combined melt and in the presence of a fluorine fluxing agent, the melting points would be lowered to some unknown degree. In fact the temperature must necessarily have been lower than that of the granite intrusive, which may have a melting point at atmospheric pressure of 1,250° C (3, p. 83), and possibly lower in the case of Aguilar, again because of the presence of fluorine. This indicates that the temperature of silicate formation may have been in the neighborhood of 1,000° C, and in any case higher than the temperature of hypothermal ore deposition. Lindgren (11) gives the range for pyrometasomatic replacement at between 400 and 600° C. Brown (5, p. 86) states that pyrrhotite, and perhaps chalcopyrite, may have a range up to 800° C. The state of fluidity which is believed to have existed in the Aguilar rocks at the time of alteration leads to the supposition that the rock temperature was only slightly below that of the granite, which must have been in a similar fluid state. No evidence has been found

to show whether the fluidity was one of solution or of fusion, but the high temperature suggests fusion.

Although the alteration is considered to be largely contact metamorphic requiring only heat and pressure from the granite, the existence of some channelways were necessary for the movement of the small quantities of the pyrometasomatic substances. As the West Branch fault was not yet in existence, a deep seated source is improbable. The substances could have found a pathway from the adjacent granite along faults of the Canedo system, or through brecciated parts of the sediments, now unrecognizable because of obliteration by the silicates or other contact effects. According to Schmitt (12, p. 136) such obliteration is a common phenomenon in contact pyrometasomatic deposits.

Relationship of the Tactite to the Granite.

Within the area a few hundred meters from the granite contact, some diminution in the strength of the silication is noted as the distance from the contact increases. The strongest alteration appears to be in the hanging wall of Bed X, Bed 1, and Bed 2, where these beds are within 100 or 150 m from the granite. Where Beds 3 and 4 are at greater distances, the alteration is weaker, even though Bed 4 is more calcareous than any of the others.

ORE DEPOSITS.

The ore bodies are all of tabular form either controlled by stratigraphic horizons, or shear zones, or both. As previously explained, the bedded deposits occur chiefly in the south end of the mine. To the north the ore-bearing horizons are successively truncated by the West Branch fault, and north of coordinate 3,400 north (Fig. 4) replacement occurs along the footwall of the fault, in the Footwall quartzite. Actually, favorable calcareous strata in the truncated quartzite contain most of the ore, and areas along the shear zone exist where sheared siliceous rocks contain little or no mineralization.

Mineralization.

In the order of their abundance, the ore minerals include reddish and yellow sphalerite, marmatite, galena, pyrrhotite, chalcopyrite, pyrite, arsenopyrite, and an unidentified silver mineral which may be either silver-bearing tetrahedrite or ruby silver. Pyrrhotite and chalcopyrite are apparent megascopically, but they and the remaining iron minerals occur in minor amounts. The gangue is composed of quartz, silicate minerals, and calcite. Both sedimentary and introduced quartz are present, the latter in places is sometimes in the form of large masses of vein quartz in the shear zone.

The marmatite at Aguilar generally contains inclusions of pyrrhotite and chalcopyrite from 0.01 to 0.02 mm in diameter. These are believed by Brown to be due to "ex-solution" (5, p. 47) from the marmatite as the mineral cooled after deposition. Such inclusions are never found in the lighter colored sphalerite.

In detail, the ore mineralization is deposited chiefly in the form of stringers and veinlets from a centimeter to a meter in width. In the more favorable areas the mineralization spreads out and replaces the beddings in masses of stringers and disseminated ore many meters in width, and tens of meters in longitudinal and vertical extent. The larger bodies are generally in the bedded deposits of Beds 2, 3 and 4, but one such mass occurs in the Footwall quartzite at coordinate 3,400 north just below the mine level shown in Figures 3 and 4. This ore body has a maximum thickness of 25 m and a length of 150 m. It is contiguous with the shear zone ore, but is actually formed in a favorable horizon which extends into the footwall.

Paragenesis.

The paragenesis of the deposit has been covered by Brown (4, 5) who found that the first depositions were clearly pyrite, pyrrhotite and chalcopyrite, followed closely by marmatite. As the deposition of the zinc sulphides progressed, their character changed from the iron-rich marmatite to red sphalerite, and finally to the clear yellow variety of sphalerite. About midway during the zinc deposition the galena began to come in. The sphalerite deposition is believed to have continued slightly longer than the galena, as small amounts of yellow sphalerite are found in polished sections to be later. The silver mineral is later than all others, with the possible exception of arsenopyrite, which was seen only in a few sections, where there were indications that it was early. Recently, it has been uncovered in small masses 50 cm or so in extent in the shear zone of the north end of the mine. Its relationship to the paragenesis is uncertain, but the masses show no galena content, indicating that it was later than the ore minerals.

Ore Types.

In both the bedded and the shear zone ore bodies most of the mineralization can be classed as replacement. A less important type of mineralization appears to have filled breccia cracks and other openings in the more siliceous rocks. The stringers are normally less than a meter in extent with no regular orientation. Substantial areas of the Footwall quartzite in the south end of the mine are mineralized in this manner, but rarely is the grade sufficient to provide minable ore.

Factors Influencing Localization of Ore.

Calcareous and Silicated Rocks.—The calcareous quartzite and silicated rocks are the fundamental cause of localization, but some preparation by shearing or brecciation was necessary for deposition, which was provided chiefly by the West Branch fault movement. The ore minerals have replaced both limestone and the silicates, but there is good evidence from thin and polished sections, and megascopically, that replacement favors the calcite rather than the silicates. This is particularly evident from the fact that little limestone as such can be found in the deposit, although there are many areas of strongly sili-

cated rock which have received little or no brecciation, and contain no ore. It also seems probable that the marmatized limestones would need a lesser degree of brecciation than the tougher silicate minerals in order to provide favorable ground for deposition.

In replacing the silicates, the ore minerals show some preferences. Diopside and rhodonite are more commonly replaced than any of the others, although in the case of diopside this may be partly because of the greater relative abundance of that mineral. Wollastonite is replaced in places generally along cleavage cracks between the blades. A few specimens have been found in which the wollastonite has been replaced almost completely by galena in a form resembling pseudomorphs after the original. Garnet is rarely replaced. These preferences probably depend on the physical properties of the various minerals, and that the tougher minerals fractured in a favorable manner, while the more flexible wollastonite did not.

West Branch Fault.—The West Branch fault in its intersection with the calcareous beds, gave rise to the most favorable localities for the deposition of the ore bodies, as well as the channel by which the mineralizers entered. The shear zone in the north end of the mine shows its effect clearly. Although the zone is in many cases 10 to 20 m in the footwall of the actual fault, the trend of most of the ore deposition is parallel to the fault, and in many cases the ore crosses the stratification of the rock. As mentioned, rock character exerts much influence, as shown by bulges of ore into favorable strata in the footwall. However, these bulges rarely extend more than a few meters from the main ore zone, showing rather definitely that replacement does not occur beyond the effects of the fault.

In the south end of the mine, where the favorable rocks are more extensive, replacement proceeded much farther from the fault. The ore beds lay between members of less competent hornfels, which probably allowed them to move and brecciate under stress to a greater degree than the footwall quartzite, Even so, the strongest mineralization in these beds is normally close to their planes of truncation by the West Branch fault. This is particularly noticeable in Bed 4, where this horizon is parallel to the fault for about 150 m, and at about 15 to 25 m distant from it. Here, a large body of good grade ore has been mined. In the southern extension of the bed where it swings toward the southeast away from the fault, the mineralization becomes low grade, and much of it is too poor to be classed as ore.

Canedo Fault System.—There is reason to believe that the Canedo faulting had some effect on the general brecciation of the rock and influence on ore deposition. However, there are no signs of shear zone ore along their immediate walls. The ore of Bed 3 in the south end of the mine seems to weaken and become more sporadic, progressing up the dip of the formation from its intersection with the Inclinada fault. As mentioned, the evidence shows that the movements on the faults began before the formation of the silicates, and that whatever shearing was produced was filled and obliterated.

East Dipping Shear.—With the exception of the shearing parallel to the West Branch fault, the east dipping shear is the only joint system that has any regularity. It strikes about north-south and dips 45° E into the granite.

It is post-silicate and pre-ore, since fine cracks in the silicates following the trend are sometimes seen with ore mineralization replacing along them. A puzzling fact is that the granite dikes almost always follow the same trend. It seems unlikely that these dikes were intruded after the silication, but probable that the shearing started early and continued into a post-silicate age. The latest phase of the shearing is believed to be connected with the B-3 fault movement. The large ore body at coordinate 3,400 north, mentioned under "Mineralization," overlies the B-3 fault, and there are signs that the favorable bedding was affected by the east dipping shear, particularly as the best ore is close to the fault.

Folds.—Folded structures are mentioned as a negative factor rather than a favorable one in ore localization. Obviously, all folds were formed very early and at great depth. Brecciation probably occurred, but it was later obliterated by the contact metamorphic effects. In some cases the folding pressed out the less competent limey rocks, which had not yet been silicated, as exemplified in Bed 1 on the anticline at 3,050 north (Fig. 3). Folds are important localizers only where they are truncated by post-silicate faulting.

Distribution of Metal Values and Zoning.

The ratio of the zinc assay to the lead is rather erratic throughout the deposit, with the important exception that the shear zone ore carries a higher proportion of lead than the bedded deposits of the south end. The average ratio for the shear zone (Zn divided by % Pb) is about 0.9, whereas that for the south end is 1.7. The extremes for all ore bodies are from 0.21 to 2.66. The higher zinc zone in the south end appears to be more or less vertical, suggesting the possibility that the initial channelway for the ore was in that area, and that the mineralization later spread to the north, depositing a higher proportion of lead values. Zoning is further suggested from the fact that relatively more arsenopyrite, which may indicate lower temperature deposition, occurs in the north end.

A regular vertical change in the ratio showing an increase in the zinc content in depth, has not been detected. In fact, the lowest known ore, which was cut in a drill hole, has a zinc-lead ratio much lower than average.

If the horizontal variations reflect zoning conditions, they bear no discernable relationship to the granite, but rather to an ore channel on the plane of the West Branch fault.

The quantitative relationship between the marmatite and the light colored sphalerite in various parts of the deposit, has not been studied in detail. However, the lower grade of zinc concentrates made during periods when the shear zone has supplied a part of the mill heads, shows that this zone carries considerable marmatite. Thus, it may be that the high zinc ratio in the south end is partially the result of late yellow sphalerite. This may indicate an ore channel, but does not fit in very well with the accepted theory of zoning.

GENESIS OF THE DEPOSIT AND ITS AGE RELATIONSHIPS.

The regional geological structure, as well as that of the mine, provide some evidence for dating the Andean mountain building period, the intrusives, and the ore mineralization.

Age of Mountain Building.

In the neighborhood of Aguilar, the Paleozoic, Mesozoic and Tertiary rocks are all roughly concordant, pointing to only one general period of mountain building in the late Tertiary. The youngest rocks exposed below the post-Paleozoic erosion surface near Aguilar are the lower Ordovician Cajas rocks. Some 100 km to the southeast of Aguilar, at an elevation of about 1,500 m (4,900 ft), Angelelli (2) reports fossils of upper Silurian age in formations overlain by what are believed to be Devonian rocks. Devonian fossils are reported by Lindgren (10) at Viacha, Bolivia, 700 km north of Aguilar. Chace (6) states that similar rocks, probably Devonian, outcrop at Oruro and Llalagua, Bolivia, about 500 km north of Aguilar. So far as is known to the author, no rocks younger than Ordovician have been found on the altiplano of northwest Argentina. Thus, there is good reason to believe that an uplift occurred in the latter area either in early Silurian, or between the Paleozoic and the Mesozoic. It seems more likely that the latter is the case, and that the late Paleozoic sediments were eroded.

Because of the scarcity of fossils in the Tertiary near Aguilar, the dating of the Andean mountain building period cannot be established with certainty closer than late Tertiary. However, the presence of boulders containing fossils of middle Tertiary in the folded conglomerates of the higher horizons shows that the mountain building probably began earlier than late Tertiary, and continued over some appreciable length of geological time. Although precise evidence is not available, this dating corresponds in general to the conclusions of Ahlfeld (1), and some other recent students of Andean geology, who believe that the folding began some time prior to the Pliocene. This conclusion is at variance with Berry (3), who estimated that the folding began in the Pliocene and continued into the Pleistocene on the basis of intrusions into horizons bearing fossils which were reported by him to be of Pliocene age.

The above facts and inferences, together with evidence in the relationships of the faulting, contact metamorphism, and mineralization of the Aguilar mine, give a sequence of geological events since the Precambrian as follows:

1. Sedimentation of the Paleozoic rocks.
2. Uplift and erosion in the north-west Argentine area.
3. Sedimentation of Mesozoic and early Tertiary rocks with little or no folding.
4. Beginning of the Andean mountain building in middle Tertiary, mostly folding, including the formation of the Aguilar anticline.
5. Intrusion of the Abra Laite granite.
6. Intrusion of the Aguilar granite into the Aguilar anticline, probably continuing through the following events:
   a. Further contortion of the sediments surrounding the granite.
   b. Beginning of the Canedo fault system due to the upward pressure from the granite.
   c. Formation of the contact and pyrometasomatic alteration near the granite.

d. Formation of the Aguilar, West Branch, and other regional block faults, probably due to regional adjustments toward the close of the mountain building period.
e. Formation of the east-west Laguna faults before the granite had completely solidified.

7. Introduction of the ore mineralization, which rose along the West Branch fault and became deposited in the favorable areas.
8. Some continuation of the fault movements of the Canedo system.

The dating of the Abra Laite granite as prior to the Aguilar is based on the fact that the former intrusive shows strong porphyritic texture near its borders, whereas the latter does not, except slight development on its eastern contact. This indicates that the Abra Laite granite was intruded into relatively cold rocks, and that the Aguilar came into rocks already warmed by the preceding intrusive.

The fact that the Tertiary rocks east of the Aguilar fault, and close to the granite contact, show no signs of contact alteration indicates that this fault and the associated West Branch occurred after the metamorphism had taken place.

Source of Ore Mineralization.

The available evidence points to the West Branch fault as the most likely channelway followed by the ore fluids, and that the source was a deep seated one. It is notable that the Aguilar deposit is located on the strike of this fault at a point where its displacement is believed to be a maximum.

The theory that the ore came directly from the granite, or through the Canedo system which probably cuts the granite at comparatively shallow depths, has been considered. It has been pointed out before, however, that any brecciated zone connected with the granite, and also the pre-silicate Canedo faults, probably lost their efficiency as ore channelways by silicate filling and contact metamorphism.

The relationship of the Canedo, West Branch, and the later Laguna faulting, shows that the movement on all of these faults, with the possible exception of the B-3, was completed before the granite became completely solidified. Therefore, unless there were later pre-ore reopenings of the faults that are not discernible at present, all faulting must have been obliterated by the still fluid granite, in the same manner as the extension of the Laguna into the granite. The only one which could have escaped encroachment is the West Branch, which might have determined the limit of the intrusive to great depth, and provided a deep sheared zone.

Relationship of the Deposit to the Granite Mass.

Judging from outcrop length of the deposit, about 1,000 m, and the attitude of the ore bodies as a whole, the erosion of at least 500 m (1,650 ft) of the original deposit seems probable. A vertical depth of 350 m of the present ore bodies is known, giving a total of 850 m (2,800 ft) as a probable minimum for the vertical range of the mineralization.

The depth of the Aguilar granite already eroded is difficult to estimate. A few large inclusions of quartzite near its western contact suggest a dip on

its west flank of about 50 degrees. Most of its outcrop discloses no such inclusions. The fact that the hornfels alteration is of more or less equal intensity on both sides of the post-alteration West Branch fault suggests that the granite was relatively close to the part of the Aguilar shale now exposed on the surface west of the fault. These rocks have dropped some 3,000 m since their alteration. Thus the granite probably extended some considerable distance above the present erosion surface. These inferences lead to the belief that the original ore deposit had a position on the flank of the granite mass in tabular form, roughly on an isothermal plane surrounding the granite, and did not extend above the top of the intrusive.

Classification of the Deposit.

At Aguilar it seems quite certain that there was a considerable time interval between the contact metamorphic period and that of ore deposition. Not only was it necessary, from the nature of the two mineralizations, for the temperature to drop considerably between the phases, but also several distinct periods of faulting occurred during the interval, the West Branch, the B-3 and the Laguna. Even so, the granite was still in a hot, fluid state at the termination of the last Laguna faulting. As the silicates were sheared by the West Branch fault, it follows that they had already crystallized before the granite had completely solidified.

The time lag has been noted by Brown (5, p. 47) who says, "Since the skarn minerals were related in time to the intrusion, and since the sulphides came distinctly later, it follows that the sulphides must have appeared after the upper part, if not all, of the granite had cooled."

The situation appears to be that the silicate alteration was an incidental feature to ore deposition rather than a fundamental one. Such alteration naturally takes place in rocks that are also favorable to ore deposition, although the sources of the two are quite different. In fact, the evidence at Aguilar shows that silication is a deleterious factor rather than a favorable one, as the sulphides seem to prefer replacement of the calcite rather than the silicates.

Thus, while the deposit is associated with contact metamorphism, which suggests its classification as a "contact metasomatic deposit in limestone," its character more closely resembles that of a normal replacement deposit. The presence of high temperature pyrrhotite, which was followed by sphalerite and galena, places the temperature of deposition in the hypothermal class of deposits.

El Aguilar, F.C.G.B.,
Provincia de Jujuy,
Republica Argentina,
Feb. 23, 1950.

BIBLIOGRAPHY.

1. Ahlfeld, F., Ueber das Alter der zinnbringenden Magmengesteine Boliviens (On the age of the stanniferous rocks of Bolivia): Zentr. Miner. Abt. A., no. 2, pp. 34–38, 1937.
2. Angelelli, V., La geologia y genesis del yacimiento ferrifero de Zapla, provincia de Jujuy: Soc. Geol. Argentina, Rev. t. 1, no. 2, pp. 117–147, 1946.

3. Berry E. W., Fossil plants from Bolivia and their bearing upon the age of the eastern Andes: U. S. Nat. Mus. Proc., vol. 54, III, pp. 103–164, Washington, 1917.
4. Brown, J. S., Factors of composition and porosity in lead-zinc replacements of metamorphosed limestone: Am. Inst. Min. Met. Eng. Tech. Pub. 1194, March 1940; Trans., vol. 144, pp. 250–263, 1941.
5. Brown, J. S., Ore Genesis, the Hopewell Press, Hopewell, N. J., 1948.
6. Chace, F. M., Tin silver veins of Oruro, Bolivia (Part I): Econ. Geol., vol. 43, no. 5, pp. 333–383, 1948.
7. Groeber, P., Mineralogía y Geología, Buenos Aires, 1938.
8. Harrington, H. J., Las corrientes de barro ("mud flows") de "El Volcán," quebrada de Humahuaca, Jujuy: Soc. Geol. Argentina, Rev. t. 1, no. 2, pp. 149–165, 1946.
9. Kobayashi, T., On the *Parabolinella* fauna from the province of Jujuy, Argentina, with a note on the Olenidae: Japanese Jour. Geology and Geography, vol. 13, no. 1–2, pp. 85–102, Tokyo, 1936.
10. Lindgren, W., and Abbott, A. C., The silver-tin deposits of Oruro, Bolivia: Econ. Geol., vol. 26, pp. 453–479, 1931.
11. Lindgren, W., A suggestion for the terminology of certain mineral deposits: Econ. Geol., vol. 17, pp. 292–294, 1922.
12. Schmitt, H., The contact pyrometasomatic aureoles: Am. Inst. Min. Met. Eng. Trans., vol. 178, p. 136, 1948.
13. Sgrosso, P., Contribución al conocimiento de la minería y geología del noroeste Argentino: Argentina, Direc. Minas y Geol. Bull. 53, pp. 31–54, 1943.

GEOLOGIC FEATURES OF NORTH DAKOTA LIGNITE.[1]

WALTER B. ROE.

ABSTRACT.

North Dakota lignites occur in the Fort Union and upper part of the Lance Formations. Individual seams vary from a few inches to over forty feet in thickness. The lignite horizons are quite continuous over large areas, but the individual seam representing a particular horizon is commonly lenticular and of limited extent horizontally.

Underclays are conspicuously absent. The lignite is woody in character and brown in color. Ash is low, and sulphur conspicuously so, and moisture is high. There is indication of cyclical sedimentation.

THE lignite deposits of North Dakota underlie the western part of the state and are a part of a more extensive area which includes eastern Montana, southern Saskatchewan and small areas in northeastern Wyoming and northwestern South Dakota. The largest part of this field is, however, within the state of North Dakota. The lignite outcrops to the north, east and south and grades westward into higher rank sub-bituminous coal.

The total area underlain by lignite in North Dakota is estimated at 35,000 square miles, while the area underlain by workable beds is about 28,000 square miles. The seams are thinner and less numerous along the southeastern outcrop in North Dakota and along the south outcrop in South Dakota and are usually not workable in these areas.

The lignite occurs in the Fort Union formation and the Ludlow member of the Upper Lance formation, which makes them either Eocene or Paleocene in age.

The greater number and the thicker beds occur in the Fort Union formation which underlies the greater part of the area. The Lance formation, beyond the outcrop of the Fort Union, along the southeast and east edges of the field contains only thin and scattered beds, except in Morton, Bowman and Slope counties where some thick beds occur. Lance rocks also outcrop in the extreme southwest corner of the state along the Baker-Glendive anticline but contain no important lignite.

THE LIGNITE MEASURES.

In the extreme western part of the state, in Billings, Golden Valley and McKenzie counties, the Fort Union formation reaches its maximum thickness and is best exposed in the Little Missouri River Badlands. Approximately 1000 to 1300 feet of Fort Union strata are exposed there and contain lignite beds throughout most of this thickness. The greatest number and thickest

[1] Presented before the Society of Economic Geologists, Committee on Coal Research, El Paso Meeting, November, 1949.

beds are, however, in the lower 700 feet of the Fort Union. The upper 400 feet of the Lance in this area also contain numerous thick lignite beds as was mentioned before.

The complete Fort Union section is estimated to contain 100 beds over four feet thick. The Slope, Billings, and McKenzie County area contains an aggregate of 192 feet of lignite in beds over four feet thick. At Tepee Bluff on the Little Missouri River, the highest single section, which is 584 feet high, contains twenty beds, some of which are, of course, mere streaks a few inches thick.

The principal structural features of the lignite area are the Baker-Glendive anticline in southwestern North Dakota and the Williston Basin in central western North Dakota. The strata dip inward toward the Williston Basin from the north, east and south and eastward and northeast away from the Baker-Glendive anticline. Dips vary from five to fifty feet per mile, with local reversals quite common. The average, however, is about twenty feet per mile. The strata are hence quite flat lying and form a rather gently dipping undulating surface.

The Fort Union and Ludlow strata are comprised of a repetition of shales, sandstones and lignite beds. The prevailing colors of the shales and sandstones, at the surface, are ash gray and yellow. The upper part of the Fort Union, above, and the Ludlow, below, are somewhat darker gray than the lower Fort Union in the middle of the section.

The whole lignite section is characterized by many beds of pink to red baked shale formed by the heat of burning lignite. This baked shale is locally called "scoria" or "clinker," the former name referring usually to the shale baked to a red brick-like consistency, while the latter refers to a more completely fused and slag-like material. This scoria is formed by the baking of the clay or shale immediately above the lignite seam by the burning of the lignite in place. The base of the scoria generally lies at about the horizon of the base of the original lignite, providing the whole seam has burned, but seldom extends below the lignite, the heat being entirely expended upward. The base of the lignite, if completely burned, is commonly marked by several inches of ash from the lignite bed. The scoria may extend for forty feet or more above the lignite and is a very conspicuous feature of the landscape in the lignite areas, particularly in the greatly eroded badlands. Several areas of lignite are burning at the present time and enormous areas of lignite have been thus burned out.

The Fort Union strata are really more uniform in color than the outcrops indicate. Many color variations seen at the outcrop do not appear in drill cuttings, which usually show a pale bluish gray color. The yellows and browns seen at the outcrop appear to be weathering features caused by oxidation of iron which was under reducing conditions within the formation.

The sandstones are mostly soft, thin, and lenticular. Locally they have been recemented to an almost quartzitic character, but this is a purely local feature. They are dirty, often containing fifty percent silt and clay. The principal constituents are quartz, muscovite, limonitic material, a few heavy minerals, and rock and lignite fragments. Color is usually gray on fresh

fractures, and may be quite dark if lignite particles are abundant. Weathered surfaces tend to be yellowish due to oxidation of the iron content. They are reasonably well sorted, the quartz grains being fairly uniform in size and somewhat rounded and the muscovite small and usually clear. Heavy minerals are apparent only on microscopic examination and are not abundant. The rock and lignite fragments vary more in size. Some contain enough rock fragments to make the sandstone conglomeratic and they do not show evidence of long transportation. The sandstones represent about twenty-five percent of the section.

The bluish gray clay or shale is the most abundant rock, making up about sixty percent of the section. Its color, as seen in drill holes, is an extremely uniform blue-gray, so much so that the drillers automatically note any variation as being unusual. The principal variation is to a brown which is probably due to some oxidation of the iron content. The shales vary in hardness, but as a rule are quite soft. They are, of course, hardest when dry but become quite soft and soapy on contact with water. Thin bentonitic layers are present, which are much lighter in color, often white. A brown fissile phase occurs just above and below the lignite contacts, but this again is hard to find in the drillings and may be a surface variation. Quartz, silt, and sand occur as impurities, as do carbonaceous material and lignite particles. Some are moderately calcareous but more often not so. Ironstone concretions occur near the middle of the shale members, particularly in the thicker ones. Limestone concretions are also common, at the same horizons; these are the only really calcareous parts of the entire section. These concretions are often as large as two or three feet in diameter, usually flattened vertically and elongated along one horizontal axis. They are light gray on fresh fractures, weather white, and are not fossiliferous. The ironstone concretions are brown to black and weather to limonite and are smaller than the limestone concretions, their size usually being measured in inches.

The brown fissile shale occurs just above and below the seams of lignite. It is brownish-gray, light brown to brownish-black in color and occurs very consistently just above and below the contacts between the blue-gray shale and the lignite. It is always fissile in character and only a few inches thick and appears to be a variation of the blue shale as the lignite is approached. The contact with the lignite is sharp but the contact with the typical blue shale is gradational. There is doubt as to whether this is a surface or weathering condition at the outcrop or a normal feature found in the body of the rock. It may be a weathering variation of a more carbonaceous part of the blue shale at the lignite contact. It is seen in almost all outcrops, even fresh cuts, but is not seen in the drill cuttings. It contains considerable silt and secondary gypsum crystals are abundant but it is not calcareous. The brown shale represents about five percent of the section.

THE LIGNITE BEDS.

The lignite beds represent approximately ten percent of the aggregate thickness of the lignite bearing part of the Fort Union and Ludlow formations. This can be seen in the Badlands areas; and in a water well at Hazen in Mercer

County, which reached the Fox Hills sandstone at 1002 feet, there was over 100 feet of lignite in seams over 10 feet thick, plus several thinner ones.

The North Dakota lignite is classified as a brown lignite. Locally it exhibits a black, lustrous appearance but this, contrary to what might be expected, is of lower grade than the brown type. This variety seems to owe its blackness and luster to a higher contamination of shaley material and tends to become a "blackjack" or "boney" lignite, with much higher ash content.

The typical brown variety has a woody appearance, breaking quite easily in two planes, as along the grain of the wood, but with difficulty in the third plane. This often gives it a splintery appearance where this structure is very well developed. At Bowman a seam about 35 feet thick is mined near the bottom of which is several feet of very woody lignite. This lignite breaks out parallel to the bedding in layers about one inch thick and vertically in one plane in pieces about six inches to a foot wide. This gives it the appearance of planks and it is called "Plank lignite" by the miners. These planks split parallel to the "grain" very easily, show the grain of the original wood, and knots are quite conspicuous. Coalified stumps are fairly common within the lignite and locally the upper surface of the seam is covered by a mat of silicified logs. These apparently were the last trees to fall on the surface of the coal swamp and became petrified rather than coalified. They are flattened, being about 18 inches by 6 inches in cross section with bark and leaf scars well preserved. It is not uncommon to find a branch on one of these logs extending down into the lignite, the part within the seam being coalified and the part above the lignite silicified. Roots are occasionally seen penetrating the shale strata below the lignite, true underclays being absent. These, however, are coalified the same as the seam itself, rather than being silicified, as are the branches and trunks on top of the lignite. The lignite is composed of approximately 75 to 85 percent trunks, branches and woody material little altered.

The lignite becomes more black in color on weathering than it is in its unweathered state. When it so weathers, the lower ash lignite takes on a glossy, *bright* black appearance, while the higher ash variety weathers to a *dull* black color. Thus, lignites that look alike in the unweathered, brown, woody state can be more easily distinguished in the weathered outcrop.

Some characteristics of the mineral matter in lignites, which are different from older coals, are interesting. The trees from which the lignite was formed were relatively modern forms, largely conifers. The mineral matter in these modern trees runs high in lime and magnesia and as a consequence the lignite ash is high in calcium and magnesium. Also in the lower ash lignites, less than five percent ash, where the inherent ash becomes a large percentage of the total, the calcium and magnesium are particularly high. This highly basic ash is in contrast to the more acid alumina and silica ash of the older coals, formed from lower type plants.

In the higher ash lignites, over five percent ash, the ash runs higher in alkalies, silica, and alumina, but it is still more basic than the ash characteristic of the older coals.

The ash content and composition of the lignites have a definite relation to their position in respect to drainage. Lignites from well-drained areas have lower ash content and a higher ash fusion temperature, 2350° to 2450° F, than those from poorly drained areas. Those from well-drained areas are leached of the alkali, silica, and alumina, reducing the total ash and also the elements which tend to flux one another. This increases the fusion temperature of the total ash, which is then largely the inherent high calcium-magnesium ash. Those from poorly drained areas, however, run higher in ash and lower in fusion temperature, 2000° F, due to redeposition of the alkalies largely as sodium sulphate.

The lignites which are commercially mined are very clean as compared with higher rank coals, in the interior basins and with many in the Appalachian Region. This contrast is probably due, in part, to the fact that the dirty lignites are not mined, but this is not the whole story. Examination and sampling of many outcrops show that the lignite beds are clean, if partings are excluded. The inherent ash in actual combination with the plant material is low, except in those few black-boney beds mentioned before.

About the only source of extraneous ash is in the partings of interbedded shale and clay. Clay-veins, horsebacks, etc., which are common in some fields are absent in North Dakota, probably because the beds have been little disturbed and no cracks have developed to provide a place for such fillings.

Sulphur is conspicuously low and is usually less than one percent and often less than one-half percent. Visible pyrite is very uncommon as are any of the other common metallic sulphides. Gypsum is the only common source of sulphur and this is much less common in the lignite than in the associated shales. The gypsum occurs as fillings in shrinkage cracks but is only of local occurrence in very poorly drained places. Calcite and siderite, which are quite common in some other coal fields as crack fillings, are very uncommon.

The following four typical analyses of lignites, being commercially mined from four scattered locations and from different seams, will give a good idea of their general character.

1. Mercer County
Beulah Bed

	As received	Dry
Moisture	37.8	—
Volatile	26.6	42.8
Fixed carbon	30.4	48.9
Ash	5.2	8.3
B.T.U. per lb.	6810	10,960
Sulphur	0.4	0.7

Ash fusion temperature

Initial deformation	2420° F
Softening	2460° F
Fluid	2510° F

2. McLean County
Garrison Creek Bed

	As received	Dry
Moisture	39.5	—
Volatile	27.3	45.1
Fixed carbon	29.4	48.6
Ash	3.8	6.3
B.T.U. per lb.	6810	11,250
Sulphur	0.4	0.6

Ash fusion temperature

Initial deformation	2395° F
Softening	2440° F
Fluid	2455° F

3. Ward County
Coteau Bed

	As received	Dry
Moisture	39.1	—
Volatile	26.7	43.9
Fixed carbon	30.3	49.8
Ash	3.9	6.3
B.T.U. per lb.	6810	11,180
Sulphur	0.2	0.4

Ash fusion temperature

Initial deformation	2400° F
Softening	2560° F
Fluid	2620° F

4. Burke County
Bed unknown

	As received	Dry
Moisture	36.1	—
Volatile	25.9	40.6
Fixed carbon	32.3	50.6
Ash	5.7	8.8
B.T.U. per lb.	7180	11,230
Sulphur	0.4	0.6

Ash fusion temperature

Initial deformation	2150° F
Softening	2190° F
Fluid	2220° F

The foregoing first three analyses are from well drained areas and show the high ash fusion temperatures from such locations.

Sample 4 is from a more poorly drained area and shows the lower ash fusion temperature from such a location.

The beds of lignite vary in thickness from mere streaks to over forty feet, the thickest occurrence being forty-four feet, without a parting. About a mile west of this occurrence, sixty feet of lignite is reported, in a small slope mine. The upper thirty feet probably corresponds to the forty-four feet mentioned above; the lower thirty feet, below the floor of the mine, and separated by a thin parting from the upper thirty feet, probably represents another thick seam, which usually is found some forty or fifty feet lower in the section.

Thin streaks of lignite occur in every few feet of the section and it is sometimes difficult to determine whether they are splits of a thick seam or individual seams. The extremely thick seams are commonly split, but many from 10 to 20 feet thick do occur without partings. In Mercer County a seam from 12 to 20 feet thick occurs without a parting over many square miles. The Coteau bed in Ward, McHenry, and McLean counties is 14 to 16 feet thick over many square miles, but does have a parting locally.

The horizons at which the lignites occur are quite continuous, but the individual beds may thin greatly or almost pinch out before they thicken again, without the horizon being entirely lost. Some individual horizons have been traced over areas of 25 by 25 miles square and in the Little Missouri River Badlands for 50 miles in one direction.

It appears as though the many swamps in which the plant material accumulated were usually connected during times of swamp conditions, but accumulation was faster in some places than in others and the bottom and subsidence were irregular, making the depth of accumulation of swamp material irregular. Apparently, however, there were definite times of accumulation over the entire area, no matter how varying in amount, with definite lapses in swamp conditions between, rather than there being accumulation at different times in different parts of the area with no connection between.

Sedimentation seems to have been quite continuous throughout Fort Union time with one cycle of lignite deposition grading into the next above without any appreciable erosion interval between. Variations in elevation and subsidence were enough to cause the deposition of the varying succession of sandstones, shales and lignites, but not enough to bring any large areas above water. Hence there is no evidence of channeling or the deposition of a channel sandstone of a succeeding cycle on an erosion surface of the preceding one.

Of the 28,000 square miles underlain by lignite in North Dakota, it is estimated that 15,000 are glaciated. This glaciated area is in the north and along the northeastern outcrop of the lignite area. All of the area north and east of the Missouri River has been glaciated and some to the southwest. The boundary of glaciation across the lignite area roughly parallels the Missouri River some miles to the southwest of that stream.

The principal effect of glaciation has been the masking of a bed rock topography, similar to the surface in the unglaciated area, by a thin to moderately heavy mantle of drift.

Along the northeast outcrop of the lignite area, however, some direct effect of the ice on the lignite can be seen. Along this edge of the lignite field, the outcrop is from a mile to five miles to the northeast or "iceward" facing side of the northeast toe of the Altamont Moraine, which here trends northwest to southeast. The outcrop itself is covered by thin ground moraine and more recent lake deposits of Lake Souris, which occupied the area northeast of the Altamont Moraine, after the retreat of the ice.

The northeast facing outcrop of the lignite was exposed to the ice and here is directly across the path of its advance. The drift in this area contains abundant lignite particles and often large pieces of "float" several feet in extent, which are large enough to be drilled through in prospecting and mistaken for solid lignite in place.

The Coteau bed which outcrops here, averages about 14 feet thick. This outcrop has been observed with 12 feet of crushed lignite pushed up over the top of it. This is apparently due to crushing by the overriding ice.

The torrential runoff from Lake Souris has cut an erosion pattern of "spillways" in the Fort Union bedrock later than the post Fort Union erosion, but earlier than the present drainage pattern. These "spillways" are filled with glacial debris and outwash.

TRUAX TRAER COAL CO.,
310 SOUTH MICHIGAN AVE.,
CHICAGO 4, ILL.,
Feb. 10, 1950.

EFFECTS OF EARTHQUAKES, TRAINS, TIDES, WINDS, AND ATMOSPHERIC PRESSURE CHANGES ON WATER IN THE GEOLOGIC FORMATIONS OF SOUTHERN FLORIDA.[1]

GARALD G. PARKER AND V. T. STRINGFIELD.

CONTENTS.

	PAGE
Abstract	441
Introduction	441
General considerations	442
Acknowledgments	444
Fluctuations caused by tides	444
Transfer of water	447
Loading and unloading effects on aquifer	448
Fluctuations caused by changes in atmospheric pressure	450
Fluctuations caused by wind or barometric effects	453
Fluctuations caused by earthquakes	454
Fluctuations caused by passing trains	459

ABSTRACT.

Determination of such fundamental hydrologic factors as the coefficients of permeability, transmissibility, and storage; areas of recharge and discharge; direction of ground-water movement; the safe yield; and other pertinent, related factors are based in part upon water-level measurements in wells. But these water-level readings, if not properly understood or weighted, may be entirely misleading. This is because water levels are neither stationary nor steadily rising (with recharge) or falling (with discharge). Water levels fluctuate as a result of several factors other than those of changes in recharge or discharge, chief among which are: (1) tides; (2) atmospheric pressure; (3) winds; (4) earthquakes; and (5) passing trains. Characteristically, artesian aquifers respond to these forces in a manner different from that of nonartesian aquifers, but in some places local geologic conditions in a nonartesian aquifer may cause water-level fluctuations ordinarily found only in artesian wells. Among the unusual features observed is a 4.5-foot fluctuation of water level in a Miami well caused by earthquake waves originating 750 miles away in the Atlantic Ocean, off the coast of the Dominican Republic. Quakes from all over the world are responsible for water-level fluctuations in this and other wells in the Miami area.

INTRODUCTION.

MANY of the recent reports on ground water contain information concerning water-level fluctuations in wells caused by effects of earthquakes, passing trains, tides, winds, and atmospheric pressure changes. Some of that infor-

[1] Published with the permission of the Director of the U. S. Geological Survey.

mation is summarized and illustrated by Meinzer.[2] The present report has been prepared primarily to present and discuss some unusual water-level fluctuations in the permeable limestone aquifers of southern Florida observed while a hurricane passed over the Gulf coast of the State, and other unusual fluctuations that resulted from numerous earthquakes in many different parts of the world. In addition, as a matter of presenting comparative material, descriptions are given of other types of fluctuations.

This paper is based chiefly on data obtained in a study of the geology and ground-water resources of southern Florida that began with an intensive investigation of the Miami area in 1939. The studies were made by the U. S. Geological Survey in cooperation with the Florida Geological Survey, Dade County, and the cities of Miami, Miami Beach, and Coral Gables; later the study was expanded by cooperation with the cities of Fort Myers, Fort Lauderdale, Lake Worth, and Fort Pierce.

General Considerations.—In order to determine the direction of ground-water movement, locate areas of recharge to and discharge from the water-bearing formations (aquifers), and evaluate the effects of recharge and discharge on the quantity of water available for use from the aquifers, measurements are made of the water levels and their fluctuations in wells. Water levels in nonartesian wells indicate the position of the water table, which represents the upper surface of the zone of saturation. Water levels or shut-in pressure in artesian wells represent the piezometric surface, which is to an artesian aquifer the counterpart of the water table to a nonartesian aquifer. The piezometric surface is the mappable representation of the height to which water levels will rise in wells that tap an artesian aquifer.

The water table and piezometric surface are seldom stationary; instead, they are constantly rising or falling, sometimes almost imperceptibly, but at other times very rapidly. The minor fluctuations are ordinarily unobserved, for they are detectable only by measuring and recording devices. Major fluctuations, such as rises of the water level to or above the land surface after heavy and continued rains or declines of the water level below the bottoms of wells, are noticeable and at times cause widespread alarm.

Major fluctuations of the water table may sometimes lead to severe economic loss. At times of extremely high water levels low-lying lands in southern Florida are flooded, drowning crops, inundating pastures, submerging many homes, business properties, roads, and airports, and causing great inconvenience—if not actual loss of life and property. On the other hand, at times of extremely low water levels the soils become desiccated; nonirrigated crops may wilt and die; the organic soils of the Everglades catch fire and burn stubbornly, destroying in a few days what has taken Nature many thousands of years to form; surface subsidence in the mucklands is accelerated;[3] and the

[2] Meinzer, O. E., Ground water in the United States, a summary: U. S. Geol. Survey Water-Supply Paper 836-D, pp. 212–220, 1939.

[3] Jones, L. A., and others, Soils, geology, and water control in the Everglades region: Florida Univ. Agr. Exper. Sta. Bull. 442, pp. 79–81, March, 1948.

salt water from the ocean moves inland both through canals and at depth in the aquifers.[4]

The burning of the organic soils in the glades is an economic loss not only to the landowner but to the tourist industry as well. At times of extensive muck fires in the Everglades the cities along the coast are often blanketed by a pall of heavy, choking smoke that drives visitors out of the area during the height of the tourist season. However, this paper is not concerned with major water-level fluctuations responsible for such conditions but, instead, discusses those interesting and little-known fluctuations caused by such widely varying forces as readjustments of the earth's surface to crustal stresses, vagaries of the weather, the position of the moon and sun, the passing of trains, and others. Although these fluctuations, ordinarily, are relatively small, records of them may be essential in the proper interpretation of ground-water geology and water resources. For example, in coastal areas the fluctuations caused by oceanic tides may be, at times and in certain places, greater than the fluctuations caused by actual change in storage of water in the aquifer; or under artesian conditions, the largest fluctuations of the water level in wells may be caused by changes in atmospheric pressure. When and where these conditions exist, they must be evaluated in order to interpret adequately the hydrologic characteristics of the aquifers and to determine the safe yield.

Tidal and barometric changes are responsible for considerable changes in load imposed on the earth's crust and the water-bearing formations in it. Artesian aquifers characteristically respond to these changes in load with responses that are readily observed by noting water-level fluctuations in wells tapping these formations. Under artesian conditions, the magnitude of fluctuations caused by tides or changes in atmospheric pressure may give significant information regarding the aquifers, such as their elasticity and compressibility.

If an artesian aquifer is competent and sufficiently rigid to resist volume change (compression and expansion) caused by loading and unloading of the tides, there are no water-level fluctuations in wells due to this force; however, under these conditions, barometric fluctuations are very effective, and wells tapping such formations may react as perfect water barometers.

If, on the other hand, artesian aquifers lack competency and rigidity, they exhibit varying but significant degrees of compressibility and elasticity, and under these conditions tidal fluctuations are large and barometric fluctuations are small.

Such information regarding the elasticity and compressibility[5] of an ar-

[4] Parker, Garald G., Salt-water encroachment in southern Florida: Am. Water Works Assoc. Jour., vol. 37, no. 6, pp. 526–542, 1945.

Brown, R. H., and Parker, Garald G., Salt-water encroachment in limestone at Silver Bluff, Miami, Fla.: ECON. GEOL., vol. 40, no 4, pp. 235–262, June–July, 1945.

[5] Meinzer, O. E., and Hard, H. A., The artesian-water supply of the Dakota sandstone in North Dakota, with special reference to the Edgeley quadrangle: U. S. Geol. Survey Water-Supply Paper 520-E, 1925.

Meinzer, O. E., Compressibility and elasticity of artesian aquifers: ECON. GEOL., vol. 23, no. 3, pp. 263–291, 1928.

Meinzer, O. E., Ground water in the United States, a summary: U. S. Geol. Survey Water-Supply Paper 836-D, p. 210, 1939.

Jacob, C. E., Notes on the elasticity of the Lloyd sand on Long Island, N. Y.: Am. Geophys. Union Trans., pt. 3, pp. 783–787, August, 1941.

tesian aquifer is significant in determining the coefficient of storage [6] and the safe yield of the aquifer [7]—modern, quantitative aspects of ground-water investigations.

Acknowledgments.—Thanks are given and appreciation is expressed to our colleagues in the U. S. Geological Survey and the Florida Geological Survey, who have aided in many ways. We are especially grateful to A. N. Sayre, Geologist in Charge, Ground Water Branch, U. S. Geological Survey, and Herman Gunter, Director, Florida Geological Survey, under whose supervision the ground-water investigations were made; to Nevin D. Hoy, District Geologist, U. S. Geological Survey, Miami, Fla., who aided materially by careful and unstinting help both in the field and office; to Russell H. Brown, Hydraulic Engineer, and C. L. McGuinness, Senior Geologist, both of the U. S. Geological Survey staff in Washington, D. C.; and to Hilton H. Cooper, Jr., District Engineer, U. S. Geological Survey, Tallahassee, Fla., for critical review of the manuscript.

FLUCTUATIONS CAUSED BY TIDES.

Tidal fluctuations in wells may be caused by ocean tides and earth tides.[8] Ocean tides may cause fluctuations of water level and artesian pressure in wells on or near the coast and earth tides may cause fluctuations not only along the coast but in the interior. However, for one reason or another, earth-tide fluctuations have not been observed in wells in Florida; therefore the following discussion relates only to fluctuations caused by ocean tides.

It is common knowledge that the ocean level is in a constant state of fluctuation, with semidiurnal high and low tides; however, it is not so commonly known that the ground-water level of coastal areas is appreciably affected by these tides. The water level in a strip along the coast rises and falls with the tides, usually with more or less lag, and the amplitude diminishes with increasing distance from the shore. Also, in the tropical zone and extending up into the oceanic temperate zones of the world, semidiurnal variations in

[6] Theis, C. V., The relation between the lowering of the piezometric surface and the rate and duration of the discharge of a well using ground-water storage: Am. Geophys. Union Trans., pt. 2, pp. 519–524, 1935.

Jacob, C. E., On the flow of water in an elastic artesian aquifer: Am. Geophys. Union Trans., pt. 2, pp. 574–586, 1940.

Wenzel, L. K., and Kazmann, R. G., Well discharge, a method of computing the quantity of water derived from storage within a given radius of a discharging well: Am. Geophys. Union Trans., pt. 6, pp. 940–951, 1944.

[7] Cooper, H. H., Jr., and Warren, M. A., The perennial yield of artesian water in the coastal area of Georgia and northeastern Florida: Econ. Geol., vol. 40, no. 4, pp. 263–282, 1945.

Sayre, A. N., Estimating safe yield as illustrated by the El Paso ground-water investigation: Econ. Geol., vol. 33, no. 7, pp. 697–708, 1938.

[8] Robinson, T. W., Earth tides shown by fluctuations of water levels in wells in New Mexico and Iowa: Am. Geophys. Union Trans., pt. 4, pp. 656–666, 1939.

Klönne, F. W., Die periodischen Schwankungen des Wasserspiegels in den inundirten Kohlenschächten von Dux in der Periode vom 8 April bis 15 September 1879: Kaiserlichen Akad. Wissenschaften, Wien, Mathematisch-Naturwissenschaftlichen Classe, B. 81, Abt. 1, Jahrg. 1880, H. 1–5, Wien, 1880.

Young, Andrew, Tidal phenomena at inland bore holes near Craddock: Royal Soc. South Africa Trans., vol. 3, pt. 1, pp. 61–106, 1913.

Thompson, D. G., Report of the Committee on Underground Waters, 1937–38: Am. Geophys. Union Trans., pt. 1, p. 345, 1938.

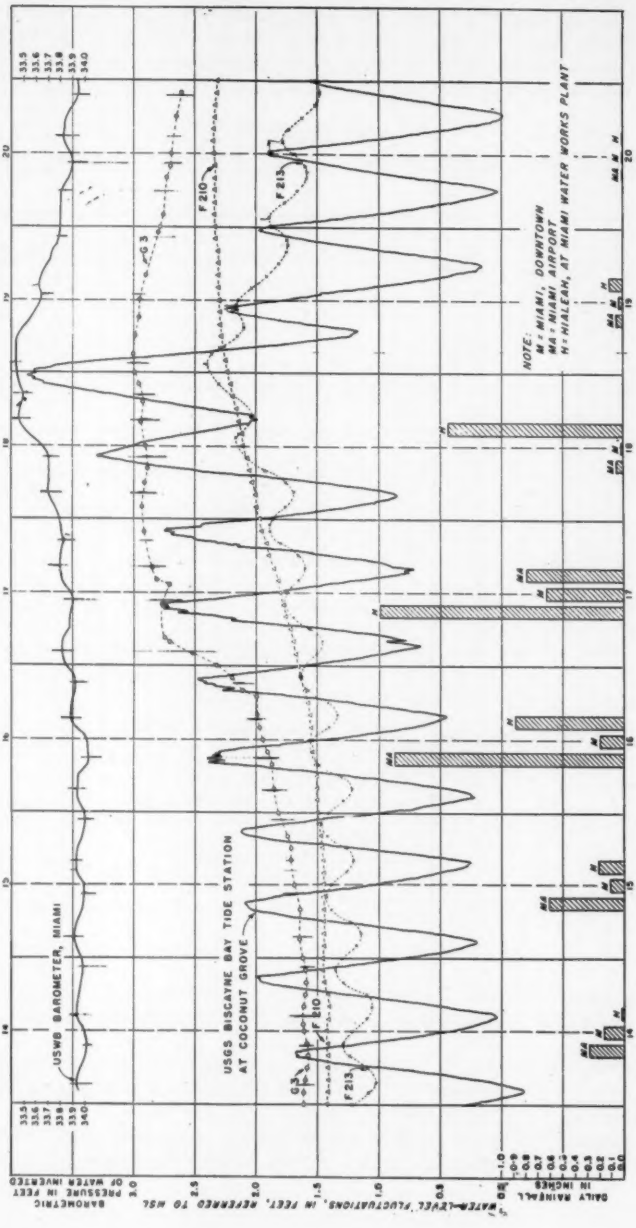
BAROMETRIC PRESSURE IN FEET OF WATER INVERTED
WATER-LEVEL FLUCTUATIONS, IN FEET, REFERRED TO MSL
DAILY RAINFALL IN INCHES
USWB BAROMETER, MIAMI
USGS BISCAYNE BAY TIDE STATION AT COCONUT GROVE
G 3
F 210
F 213
NOTE:
M: MIAMI, DOWNTOWN
MA: MIAMI, AIRPORT
H: HIALEAH, AT MIAMI WATER WORKS PLANT

FIG. 1. Graph showing water-level fluctuations, atmospheric-pressure changes, and rainfall at Miami, Fla., during hurricane of October 1944

atmospheric pressure with highs near midnight and noon and lows near 6 A.M. and 6 P.M. (Figs. 1, 5, which give typical records from the U. S. Weather Bureau microbarograph at Miami) cause water-level fluctuations that, in places, may be mistaken for effects of oceanic tides. The latter, however, oc-

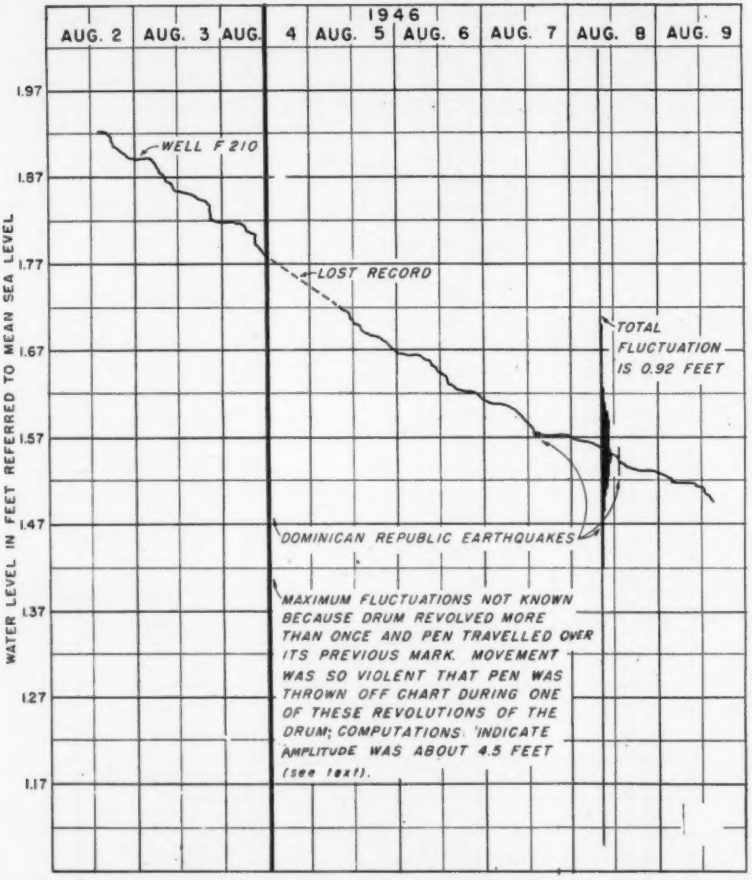

FIG. 2. Graph showing effect of earthquakes on water level in well F 210.

cur progressively about 50 minutes later each day, whereas the former are nearly constant in their time of occurrence. This difference in timing allows for separation of the two effects.

Ocean-tide fluctuations in wells may be due to one of two causes, depending upon the local geologic conditions. They may be the result of (1) actual

transfer of water between the ocean and the ground through communicating openings, such as pores and crevices, as the tide rises and falls; or (2) alternate compression and expansion of the water-bearing beds (aquifers), caused by transmission of the effect of the addition of water at high tide and the re-

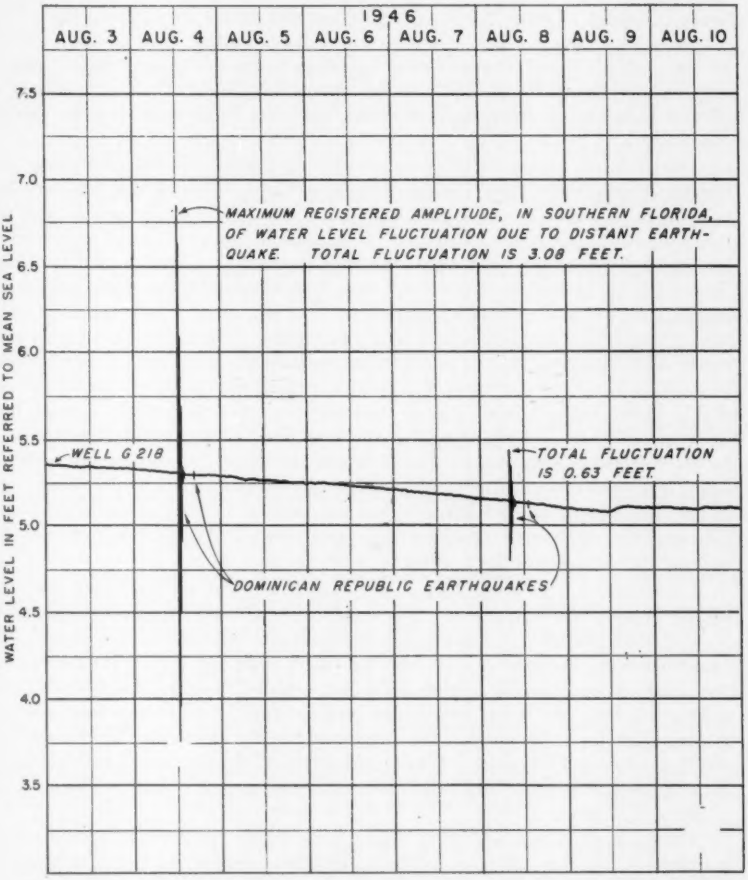

FIG. 3. Graph showing effect of earthquakes on water level in well G 218.

moval of the weight at low tide. Fluctuations caused by transfer of water may occur in shallow wells under water-table conditions near the coast.

Transfer of Water.—The ocean is the base level for both surface- and ground-water discharge. Whenever a stream level falls below that of the ocean a reversal in flow takes place in the stream, and ocean water flows in-

land until a place is reached where the levels are equal. The same thing happens to ground-water flow in the coastal aquifers. Ordinarily, ground water flows seaward or toward some nearer seaward-flowing stream that offers a steeper gradient to base level. But if, by any means, ground-water levels in the coastal zone become lowered below sea level—as may happen because of heavy pumpage or large evapo-transpiration loss during droughts—ocean water percolates inland into the aquifers and displaces the fresh ground water. In fact, owing to its greater specific gravity, ocean water may move inland long before ground-water levels decline below sea level. However, this is a phenomenon apart from consideration here, and is discussed in detail elsewhere.[9]

Figure 1 is a graph showing water-level fluctuations in Miami during the hurricane of October 1944, and also showing, among other things, the correlation between water-level fluctuations in well F 213 (69 feet deep) and in Biscayne Bay (1,320 feet away). Fluctuations in the well are in phase with, but lag slightly behind, the tidal fluctuations in the bay. The amplitude of the fluctuation in the well is considerably less than the amplitude of the tidal fluctuations in the bay, the ratio being about 1 to 7. Only a few shallow wells have been drilled at the shore line to determine the magnitude of ground-water tidal fluctuation in the nonartesian aquifer; from the data thus obtained it has been found that the ratio of ground-water fluctuation to bay-level fluctuation is variable from place to place, depending upon local geologic factors, but is not quite 1 to 1. The greatest distance that direct effects of tidal fluctuations in the bay have been observed in water-table wells in southern Florida is 6,680 feet (the observation well in which this occurs is F 179, 77 feet deep, in the Silver Bluff area of Miami), but the average maximum distance is approximately 6,400 feet. The average amplitude of the tidal fluctuations in wells at this distance is approximately 0.02 foot.

Loading and Unloading Effects on Aquifers.—Where the aquifer is overlain by impervious beds and artesian conditions exist, ocean tides are effective in producing transfer of water only through the submarine outcrop of the aquifer, which, in some places, may be many miles offshore. Under these conditions it seems unlikely that a tidal wave could be transmitted from the outcrop offshore and be recognized in a well on land. In any case, the effect of oceanic tides on artesian pressure decreases rapidly as the distance from the tidal body of water increases. The points farthest inland at which tidal fluctuations in artesian pressure were definitely observed were 0.2 mile in Florida and 1 mile in Georgia.

The geologic conditions in Florida, insofar as they affect the occurrence of the artesian aquifers, are somewhat comparable to conditions in the vicinity of

[9] Parker, Garald G., op. cit.

Brown, Russell H., and Parker, G. G., op. cit.

Stringfield, V. T., Ground-water resources of Sarasota County, Florida: Florida Geol. Survey 23d–24th Ann. Rept., pp. 167–177, 1933.

Stearns, H. T., Geology and ground-water resources of the islands of Lanai and Kahoolawe, Hawaii: Hawaii Div. Hydrography Bull. 6, pp. 77–85, 1940.

Brown, J. S., A study of coastal ground water, with special reference to Connecticut: U. S. Geol. Survey Water-Supply Paper 537, 101 pp., 7 pls., 1925.

Atlantic City, N. J., where Thompson [10] has demonstrated that fluctuations in the artesian pressure in wells drawing from an aquifer at a depth of 800 feet are due to the alternate loading and unloading in the immediate vicinity, and not to any pressure change transmitted from the submarine outcrop many miles offshore. In the coastal area of Georgia [11] where conditions are similar to

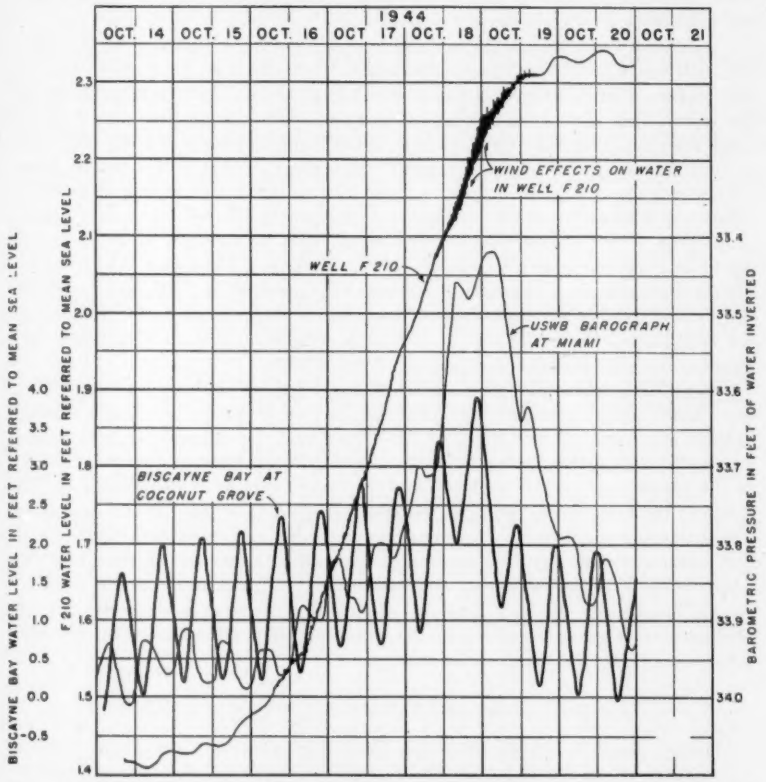

FIG. 4. Graph showing effect of hurricane-associated phenomena on water level in well F 210.

those in Florida, observations concerning the rate at which pressure effects are transmitted through an aquifer indicate that days would be required for the pressure effect of tide to be transmitted from the submarine outcrop to a well

[10] Thompson, D. G., Ground-water supplies of the Atlantic City region: New Jersey Dept. Cons. and Devel. Bull. 30, pp. 27–30, 57, 113, 1928.

[11] Warren, M. A., Artesian water in southeastern Georgia, with special reference to the coastal area: Georgia Geol. Survey Bull. 49, p. 66, 1944.

on the coast. By contrast, a transfer of water in the formation through such a distance would require years.

The maximum fluctuation observed that can be definitely attributed to the loading and unloading effect of ocean tide on artesian aquifers in Florida amounts to about 1 foot [12] in wells near the Gulf of Mexico and 2 feet [13] in wells near the Atlantic Ocean. These fluctuations are approximately half the magnitude of the tide near the wells.

Warren [14] recorded a tidal fluctuation of 4.35 feet in a well at Fort Screven, Ga., 600 feet west of the Tybee Lighthouse, when the tidal fluctuation was 9.7 feet in the Atlantic Ocean at the Tybee Light, about 1,000 feet northeast of the well. This shows a water-level fluctuation that is about 50 percent of the tidal fluctuation in the ocean at the Tybee Lighthouse, indicating that the aquifer has a tidal efficiency of about 50 percent. This is about the same efficiency as that observed for the Floridan aquifer,[15] the principal artesian aquifer of Florida, southern Alabama, and southern Georgia, in a few places in Florida where conditions are similar to those in Georgia. However, as might be expected from a knowledge of the geology of the region, Warren observed that the tidal fluctuations of artesian pressure in different parts of the coastal area of Georgia ranged from about 20 percent to 50 percent of the tidal fluctuation in the ocean. These observations indicate significant differences in the coefficient of storage in the aquifer.

In estimating the tidal efficiency of an aquifer along an irregular shore line, with tidal marshes and flats, consideration must be given to the area inundated at different stages of the tide. At the Tybee well, for example, a larger land area is flooded during spring tides than during neap tides, and the fluctuation of the water level in the well is about 7 percent larger in proportion to the range of the tide during spring tides than during neap tides. If the area over which the tide rises and falls were always the same, it is believed that the tidal fluctuations of water levels in a given well would be a certain percentage of the range of the tide during spring and neap tides. This is because the artesian aquifer is an elastic medium, and the amount it is compressed is in direct proportion to the change of loading on the surface, which, when caused by the tide, varies directly as the depth of the water.

FLUCTUATIONS CAUSED BY CHANGES IN ATMOSPHERIC PRESSURE.

Despite the fact that the shallow wells in the Miami area generally exhibit nonartesian characteristics, and therefore are considered to represent water-table conditions, some wells evidently respond to changes in atmospheric pressure. These changes are likely to be masked or interfered with by tidal changes, especially near Biscayne Bay or any of the tidal canals, and by recharge from occasional rainfall. Further, because the geologic conditions may

[12] Stringfield, V. T., Ground-water resources of Sarasota County, Florida: Florida Geol. Survey, 23d–24th Ann. Rept., p. 163, 1933.

[13] Stringfield, V. T., Artesian water in the Florida peninsula: U. S. Geol. Survey Water-Supply Paper 773-C, p. 141, 1936.

[14] Warren, M. A., op. cit., p. 74.

[15] Parker, Garald G., and others, Water resources of southeastern Florida: unpublished manuscript being processed for publication by the U. S. Geol. Survey, Washington, D. C.

cause the local confinement of ground water under artesian pressure in what is otherwise a nonartesian aquifer, no two wells respond to the same barometric changes in the same manner. Barometric fluctuations in wells have been discussed by previous writers, including Meinzer [16] and Stringfield.[17] Stringfield

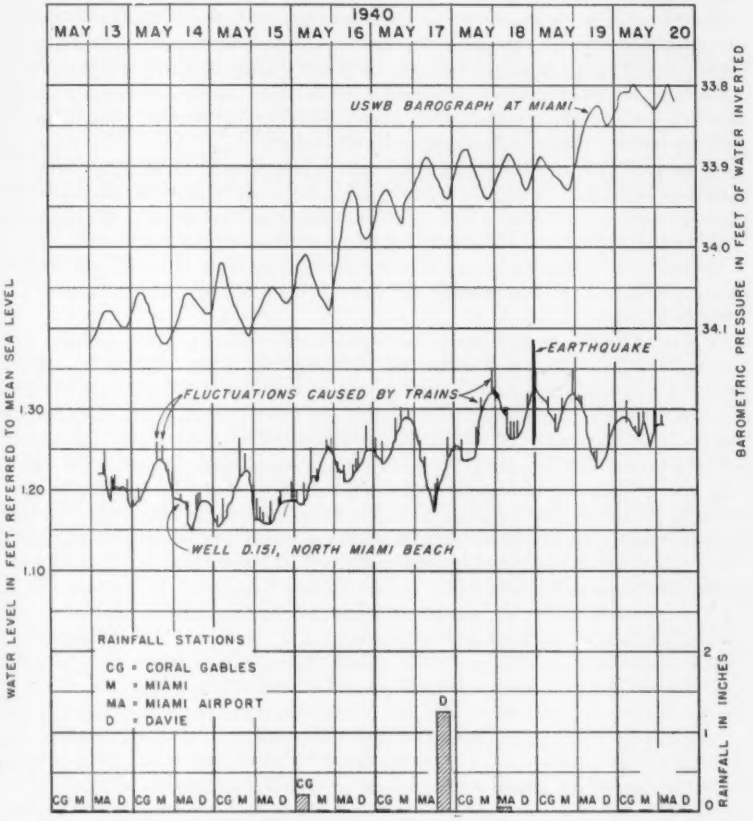

FIG. 5. Graph showing barometric fluctuations, rainfall, effects of tides, an earthquake, and passing trains on water level in well D 151.

describes the effect of changes in atmospheric pressure on water-level fluctuations in the artesian wells of Sarasota County, Fla., where there is a close relation between fluctuations of water level and atmospheric pressure. A com-

[16] Meinzer, O. E., Outline of methods for estimating ground-water supplies: U. S. Geol. Survey Water-Supply Paper 638, pp. 140–142, 1932.

[17] Stringfield, V. T., Ground-water resources of Sarasota County, Florida: Florida Geol. Survey 23d–24th Ann. Rept., pp. 159–162, 1933.

parison of the water level with the atmospheric pressure there indicates that during part of the period of record the water-level fluctuation was nearly equal in amount to the fluctuation of the atmospheric pressure, when translated into feet of water pressure, and at other times it was about half the change in atmospheric pressure. However, such differences might be expected, because the atmospheric pressure was recorded about 7 miles from the well and local differences in pressure occur in that distance. In reviewing these facts, Stringfield is of the opinion that a barograph at the well would show that the magnitude of water-level fluctuations due to changes in barometric pressure would be about half those of the barometer, indicating a barometric efficiency of about 50 percent for the aquifer.

Figure 1 shows atmospheric-pressure fluctuations at Miami, in feet of water, inverted in order to show the relation between changes in atmospheric pressure and water levels. Thus, a downward trend in the barometric curve indicates an increase in pressure and an upward curve indicates a decrease. A semidiurnal cycle averaging a little more than 0.06 foot in amplitude is apparent. Barometric fluctuations are also plotted in this same manner in Figures 4 and 5.

Figure 1 depicts hydrologic and barometric conditions at Miami during the passing of a hurricane over peninsular Florida. The record begins on October 14, 1944, during normal conditions, and continues through October 20, at which time the storm had passed out of the State. Actually, the center or "eye" of the hurricane was never closer to Miami than 120 miles. It passed over the Gulf of Mexico about 40 miles west of Wey West and about 25 miles west of Fort Myers; then it entered the mainland just south of Sarasota and made its exit near Jacksonville. Nonetheless, the atmospheric pressure was lowered enough at Miami during the early morning of October 19 to cause a water-barometer rise, compared with the pre-storm low, of about 0.54 foot on the afternoon of October 15.

The low barometric pressures associated with hurricanes cause rises of water level in very large open bodies of water, even as they do in certain wells. Part of the rise in the Biscayne Bay hydrograph is due to this factor, though most of the rise is caused by the piling up of ocean water in Biscayne Bay by the 50- to 60-mile-per-hour winds that blew from the Atlantic Ocean.

Well G 3 (Fig. 1) is a shallow well less than 10 feet deep ending in permeable oolitic limestone in the Miami well-field area of Miami Springs. Over the oolite is a mantle composed of several feet of muck and marl, materials that, when wet, prevent the passage of air through the soil above the water table and cause the well to act as a partially effective water barometer. Thus, there is a good time correlation between the semidiurnal water-level fluctuations appearing in the hydrograph for well G 3 and the inverted plot for the barometer. The gradual upward trend and diminution of the semidiurnal fluctuation of the water level, as shown by the hydrograph for G 3 beginning about noon on October 14, are caused by rainfall recharging the aquifer. Precipitation in the Miami area, representing rainfall at the Miami, Miami Airport, and Hialeah weather-observation stations, is shown by bars at the bottom of the plate.

Figure 2 shows the water level in well F 210, with semidiurnal fluctuations and several earthquake fluctuations. The semidiurnal fluctuations appearing in the hydrograph for F 210 are due to the effects of oceanic tides in Biscayne Bay. More will be said of this illustration later.

Figure 4, shows water-level fluctuations in well F 210 for the duration of the October 1944 huricane mentioned earlier; barometric fluctuations in feet of water, inverted, are plotted to the same scale, and oceanic tides in Biscayne Bay are shown on a scale one-tenth as great. It is apparent that the semidiurnal fluctuations of air pressure, as shown by the barograph, are out of phase with the fluctuations of water level in both F 210 and Biscayne Bay; that is, highs occur on the F 210 hydrograph at the time of lows on the inverted barograph record. The sharp rise of the hydrograph for F 210 beginning on the afternoon of October 15 and continuing into October 19 is principally caused by ground-water recharge from rainfall and, to a minor extent, by a temporary regional rise of the coastal water table caused by barometric and wind effects that raised the base level in Biscayne Bay.

Figure 5 shows barometric fluctuations at Miami, in feet of water, inverted together with rainfall, the effects of tides, an earthquake, and passing trains on the water level in well D 151 (an abandoned drainage well at the Peoples Water and Gas Co. plant) at North Miami Beach, on the eastern edge of the Atlantic Coastal Ridge about half a mile from tidal water in the Oleta River. The well is reported to have been 200 feet deep when drilled, but it was only 175 feet deep according to a measurement made in 1939. No casing record or driller's log is available.

The semidiurnal fluctuations of the barometric record show no correlation with those of the water level in well D 151, which are caused by oceanic tides. Numerous minor fluctuations, appearing on the hydrograph as short vertical lines above the water-level curve, are caused by the passing of trains on the nearby Florida East Coast Railroad. The fluctuation appearing near midnight on May 18 was caused by an earthquake.

The rainfall bars for the four nearest reporting weather stations indicate a relatively dry week, marked by a heavy shower at Davie on May 17. Apparently the shower was quite local, as the water level in well D 151 was not affected by this rainfall. Because no recording tidal station is located near enough to the Oleta River to be of value for correlation, it is impossible to present graphically the oceanic fluctuations that are chiefly responsible for the semidiurnal fluctuations which in this well average about 0.05 foot, nor for the larger fluctuations that also are shown.

FLUCTUATIONS CAUSED BY WIND OR BAROMETRIC EFFECTS.

Already mentioned are rises of water levels in wells, caused by hurricane winds heaping up tide waters in Biscayne Bay and in connecting tidal canals; however, the wind causes other fluctuations, such as those represented in Figure 4, on the hydrograph of well F 210. These fluctuations are minor, seldom exceeding 0.03 foot, and are caused by changing air pressures in the well above the water level. These air-pressure changes result from variations

in the velocity of the wind as it blows across the open top of the casing or past the structure housing the recorder. Paint-guns, atomizers, and air-injector pumps work on this same principle—air blows across the open mouth of a tube, the base of which is immersed in a liquid, thus creating a sufficiently low pressure in the tube to cause the liquid to rise and to be removed from the container. In wells, as a sudden gust of wind blows across the top of the casing, the air pressure in the well is immediately lowered and, as a consequence, the water level quickly rises. As the gust passes, the air pressure in the well rises (is restored to normal pressure), and the water level consequently falls. During storms, as the gusty winds alternately raise and lower the air pressure on the surface of the water in the well, the water is alternately drawn in and forced out of the bottom of the well, thus creating records such as those shown on Figure 4 for well F 210. Weather Bureau records show that the maximum wind velocity on the days when the wind-induced water-level fluctuations occurred was as follows:

October 15: 26 miles per hour from NE.
16: 32 miles per hour from N.
17: 36 miles per hour from NE.
18: 54 miles per hour from SE.
19: 65 miles per hour from S.

Sometimes these minor and very rapid fluctuations are caused by air-pressure changes in large structures housing wells, and are thus directly transmitted to the surface of the water in the wells. As the gusty wind alternately creates external pressure changes on the windward and leeward sides of the structure, there are resultant pressure changes inside. Frank C. Foley, District Geologist of the U. S. Geological Survey at Madison, Wis., reports [18] that such wind-induced fluctuations occur in a well in the basement of a large manufacturing plant in Madison. There is only normal doorway communication with the outside, and the wind has no direct access to the well. Thus, the cause is temporarily lowered atmospheric pressure within the building. It is this same phenomenon that is responsible for the commonly observed fluctuation of water level in toilet bowls during windy weather.

FLUCTUATIONS CAUSED BY EARTHQUAKES.

Earthquake-caused fluctuations in wells have been recognized for many years and have been described in several reports.[19]

Some of the most interesting, and certainly the most intriguing, of the water-table fluctuations observed in the Miami area are caused by earthquake shocks. These are shown on standard automatic water-level recorder charts by a vertical trace of the pen, ranging approximately an equal distance

[18] Personal communication, June 10, 1949.

[19] Pardee, J. T., The Montana earthquake of June 27, 1925: U. S. Geol. Survey Prof. Paper 147-b, pp. 7–23, 1927.

Leggette, R. M., and Taylor, G. H., Earthquake instrumentally recorded in artesian wells: Seismol. Soc. America Bull., vol. 25, no. 2, pp. 169–175, Stanford Univ., Calif., April, 1935.

Thomas, H. E., Fluctuations in ground-water levels: Seismol. Soc. America Bull., vol. 30, no. 2, pp. 93–97, Stanford Univ., Calif., April 1940.

above and below the point on the chart representing the water table at the time the shock occurred (Figs. 2, 3, 5). If the shocks last during a period of an hour or so, a record such as that for August 8, 1946, is made.

Water-stage recorders in use during this investigation were not designed or intended for seismographic work, and are not equipped to enable the operator to determine the direction from which the earth shock originated. The recorders are not calibrated accurately for time and can scarcely be read to a time interval of less than 15 minutes; in fact, because of this lack of accurate calibration, men who change the charts are not always as careful of precise time setting as is desired. Doubtless careless time setting of the recorder was responsible for the local recording of earth shocks apparently prior to their actual occurrence at the epicenter (Table 1). However, the recorder charts do show the approximate time that shocks arrive and reflect their magnitude, as shown by the change in water level in the well. For some of the weaker shocks, especially, the magnitude is probably dampened out by frictional resistance within the recorder itself or between the float in the well and the well casing, so that the record is not a true representation of the actual water-level fluctuation.

Table 1 lists earthquakes from 1940 to 1946, as recorded by a weekly water-stage recorder mounted on well F 210, in Miami, and also those reported by the U. S. Coast and Geodetic Survey. Well F 210, in most respects, acts as a nonpressure or nonartesian well, but to earth shocks it responds like an artesian well. Evidently there are shallow, local semiconfining lenses or layers, probably of very fine sand, in the limestone aquifer in which the well is developed. These lenses or layers do not prevent normal water-table conditions from existing in the vicinity, but to sudden earth shocks they act as a confining bed does in an artesian system. Well F 210 is only one of numerous wells in southern Florida that are known to respond to earthquake waves; however, F 210 gives the best record and in the interest of brevity is chosen as an example.

It will be noted that earthquakes from all over the world are listed in Table 1, and that often there is very little time lag between their reported time of occurrence (from U. S. Coast and Geodetic Survey reports) and their time as registered on the water-stage recorder. This is to be expected, because even the slowest of the earthquake waves—the surface or "L" waves—travel at speeds of approximately 125 miles a minute. Thus, the water-level disturbance caused by the Dominican earthquakes of August 4 and 8, 1946, should have been expected to appear in Miami about 6 minutes after the origin of the quake at the epicenter off the northern shore of the Dominican Republic. On weekly water-level recorder records this amount of time is less than that represented by the width of the mark made by the recording pen. "L" waves from distant quakes, such as those in Japan or the South Sea Islands, require about 60 to 80 minutes to travel to Miami, depending upon the location of the quake's epicenter.

The effects of the Dominican Republic earthquakes of August 4 and 8, 1946, on the water level in the Miami area are shown in Figures 2 and 3. Records from wells F 210 and G 218 are given as examples. F 210 is fitted

TABLE 1.

RECORD OF EARTHQUAKES FROM WATER-LEVEL FLUCTUATIONS IN WELL F 210, MIAMI, FLORIDA, CORRELATED WITH U. S. COAST AND GEODETIC SURVEY RECORDS, 1941–46.

Amplitude of water-level fluctuation, in Well F 210 (feet)	Date	Time (EST) of water-level fluctuation in F 210	Time (EST) of quake at locus	Locus of quake	Remarks
0.470	4/7/41	6:00–6:30 P.M.	6:29.3 P.M.	17.6° N., 78.3° W., Caribbean Sea, SW. of Jamaica.	
.052	6/26/41	10:10–10:40 A.M.	6:52.1 A.M.	13° N., 93° W., Pacific Ocean, off Guatemala.	
.013	6/27/41	1:45 P.M.	12:11.3 P.M.	16° N., 93° W., Gulf of Tehuantepec, So. Mexico	
.270	12/5/41	4:10–5 P.M.	3:46.9 P.M.	8° N., 83° W., Pacific Ocean, off N. Panama.	
.063	12/6/41	4:30–5 P.M.	4:24.6 P.M.	8° N., 83° W., Pacific Ocean, off N. Panama.	
.040	5/13/42	9:30–10 P.M.	9:13.3 P.M.	1° S., 79° W., SW. of Quito, Ecuador.	
.393	8/6/42	6:45–7:15 P.M.	6:37.0 P.M.	14.4° N., 90.9° W., near Antigua, Guatemala.	
.177	2/22/43	4:45 A.M.	4:20.8 A.M.	17.6° N., 101.3° W., Guerrero, Mexico.	
.035	4/6/43	11:45 A.M.–12:15 P.M.	11:07.1 A.M.	32° S., 70° W., near Mt. Mercedario, NW. of Valparaiso, Chile.	Heaviest shock at noon.
.018	4/19/43	10:00 A.M.	*	*	
.074	5/2/43	12:45–1:15 P.M.	12:18.2 P.M.	6.4° N., 80.1° W., Pacific Ocean, off Azuero Penin., Panama.	
.007	6/8/43	5:30 P.M.	3:42.2 P.M.	19° N., 116° E., South China Sea, between Hainan and Luzon.	
.012	6/9/43	11:30 A.M.	11:06.3 P.M.	3.0° S., 102.5° E., near Barisan Mts., Sumatra.	
.110	6/15/43	1:30–2:00 P.M.	*	*	
.010	6/15/43	3:20 P.M.	*	*	
.010	6/15/43	4:00 P.M.	*	*	
1+	7/28/43	10:00–11:45 P.M.	11:02.2 P.M.	18.9° N., 67.0° W., Rico. Atlantic Ocean, N. of Mayaguez, Puerto Rico.	Drum revolved more than once. Scale is 1:1, thus the pen retraced its mark and hides high and low marks. Successively diminishing shocks registered: 0.172′; 0.125′; 0.082′; and 0.050′.

TABLE 1—*Continued*

Amplitude of water-level fluctuation, in Well F 210 (feet)	Date	Time (EST) of water-level fluctuation in F 210	Time (EST) of quake at locus	Locus of quake	Remarks
.012	9/6/43	11:30 P.M.	10:41.5 P.M.	53.2° S., 159.4° E., Pacific Ocean, between Tasmania and New Zealand.	
.378	11/3/43	9:50–10:50 A.M.	9:32.3 A.M.	62° N., 151° W., So. of Mt. McKinley National Park, Alaska.	Greatest shock at 9:55 A.M., followed by three lesser successive shocks.
.030	11/6/43	4:05–4:50 A.M.	3:31.6 A.M.	5.5° S., 134.0° E., Banda Sea off SW. Coast of New Guinea.	Greatest shock at 4:15 A.M., both preceded and followed by lesser shocks.
.015	12/8/43	4:30–4.45 P.M.	*	*	Greatest shock at 3 P.M.
.015	12/23/43	2:50–3:10 P.M.	2:00.1 P.M.	6° S., 152° E., Pacific Ocean, SE. of New Britain.	
.029	1/10/44	3:10–4:00 P.M.	3:10.0 P.M.	18.1° N., 100.6° W., Guerrero, Mexico.	
.020	1/31/44	11:00 P.M.	11:22.7 P.M.	41° N., 31° E., S. Coast of Black Sea, Turkey.	
.008	2/3/44	7:20 A.M.	7:15.2 A.M.	59.3° N., 138.0° W., near Yakutat Southeastern Alaska.	
.007	3/31/44	2:50–3:10 P.M.	*	*	On this date at 3:34.8 P.M. a quake occurred 3° S., 81° W., in Ecuador.
.015	6/16/44	6:00 P.M.	4:51.5 P.M.	19° N., 105° W., Pacific Ocean, near Manzanillo, Mexico.	
.028	6/25/44	3:30 P.M.	*	*	
.035	6/25/44	5:15 P.M.	*	*	
.018	6/26/44	10:40 A.M.	*	*	On this date at 7:04.2 P.M. a quake occurred 54.5° N., 166.5° W., Aleutian Is.
.224	6/28/44	3:00–3:45 P.M.	2:58.9 P.M.	14.6° N., 92.6° W., Pacific Ocean, off Southern Mexico near Guatemala border.	Maximum quake at 3:10 P.M.
.016	8/3/44	6:20–7:10 A.M.	*	*	Maximum quake at 6:20 A.M.
.120	12/7/44	1:10–2:10 P.M.	12/6/44 11:35.7 P.M.	33° N., 137° E., Pacific Ocean, SE. of Osaka, Japan.	Maximum quake at 1:40 P.M.
.017	4/14/45	10:30 P.M.	4:35.2 P.M.	56° N., 164° E., Pacific Ocean, off east-central Kamchatka Peninsula.	

TABLE 1—*Continued*

Amplitude of water-level fluctuation, in Well F 210 (feet)	Date	Time (EST) of water-level fluctuation in F 210	Time (EST) of quake at locus	Locus of quake	Remarks
.006	5/19/45	7:00 A.M.	*	*	
.030	10/7/45	8:15–8:30 A.M.	8:23.4 A.M.	12.3° N., 89.0° W., Pacific Ocean, off coast of San Salvador, El Salvador.	
.057	11/27/45	6:00–7:00 P.M.	4:56.8 P.M.	Near 22° N., 62° E., Arabian Sea.	Max. quake at 6:30, preceded and followed by lesser quakes.
4.5**	8/4/46	12:30 P.M.	12:51.07 P.M.	9 miles east of Samana Peninsula, Dominican Republic.	Drum revolved several times and so rapidly that pen was eventually knocked off chart and remainder of record lost (see Figs. 2, 3).
.920	8/8/46	7:50–10:45 A.M.	8:28.4 A.M.,	9 miles east of Samana Peninsula, Dominican Republic. (Aftershock.)	Maximum quake at 8 A.M., both preceded and followed by lesser shocks (see Figs. 2, 3).
.033	8/8/46	1:00 P.M.	*	*	
.075	8/21/46	2:00–2:15 P.M.	2:17.6 P.M.	9 miles east of Samana Peninsula, Dominican Republic. (Aftershock.)	
.015	9/12/46	10:00 A.M.	*	*	On this date at 10:16.9 A.M. a quake occurred 25.5° N., 89° E., northwest Bengal.
.038	9/12/46	12:00 P.M.	*	*	
.010	9/20/46	12:45 A.M.	*	*	
.017	9/25/46	4:40 A.M.	*	*	On this date at 5:05 A.M. an aftershock of the Dominican quake occurred.
.030	10/4/46	9:45 A.M.	9:45.4 A.M.	Dominican Republic. (Aftershock.)	
.218	12/20/46	3:00–4:00 P.M.	2:19.0 P.M.	134° E., 33° N., East coast of Shikoku Id., Japan.	Max. quake about 3:30 P.M. Series of lesser quakes both preceded and followed main quake.

* Not recorded on seismographs elsewhere.
** Calculated. See text and figure 2.

with a recorder having a gear ratio of 1 : 1 (1-foot change of water level causes a corresponding 1-foot change on the recorder graph), whereas G 218 has a 5 : 1 recorder ratio (5-foot change of water level causes a corresponding 1-foot change on the recorder graph).

The record for F 210 (Fig. 2) shows a continuous vertical line on the chart for the quake of August 4, thus indicating that the fluctuation was more than 1 foot, but because the pen overlapped its first mark there is no means of directly determining the amplitude of the total fluctuation. The record is broken after this quake, because the movement of the recorder drum—in response to the sudden change in water level—was so rapid that when the pen reached the overlap of the chart paper it was thrown clear of contact. The pen was reset the following morning.

On August 8, a second series of violent shocks occurred, which lasted more than 3 hours and caused a maximum recorded amplitude of 0.92 foot shortly after 8 A.M.

The record for G 218 shows that the August 4 shock caused a fluctuation of water level in that well of 3.08 feet, and the August 8 shock a fluctuation of 0.63 foot. If the shocks are proportional in the two wells, the amplitude of the fluctuation in F 210 on August 4 would have been 4.5 feet.

This fluctuation of 3.08 feet in G 218 on August 4, 1946, is the greatest measured fluctuation of the water level in southern Florida caused by distant earthquakes, but the calculated fluctuation of 4.5 feet for F 210 probably is essentially correct and may be regarded as the maximum known fluctuation caused by distant quakes.

The record for D 151 for the week of May 13–20, 1940 (Fig. 5), shows a typical earthquake fluctuation occurring between 11 : 15 and 12 P.M. on May 18, the maximum fluctuation of 0.13 foot occurring at about 11 : 50 P.M.

In addition to recording many of the numerous quakes reported by regular seismological stations, water-stage recorders in southern Florida record many unreported tremors. Table 1 lists 16 of these, ranging in amount of fluctuation from 0.006 to 0.038 foot. It is believed that these minor shocks represent minute adjustments of the earth's crust, possibly along the nearby margin of the Floridian Plateau. The fact that they are not reported by the regular seismological stations indicates their local character.

FLUCTUATIONS CAUSED BY PASSING TRAINS.

In only one well in the Miami area have the effects of passing trains on the water level in wells been recorded. Probably others exhibit this same phenomenon, but as they are not equipped with recorders the effects have not been observed. Figure 5 shows numerous vertical lines representing sudden rises and almost immediate declines of the water level in well D 151 as the trains traverse the nearby Florida East Coast Railroad. These fluctuations are compressional effects caused by the weight of the passing train upon the elastic aquifer. As a train approaches, the water level rises in the well; then, as the train passes by, the water level declines to normal. Long, heavy freight trains cause the largest fluctuations (as great as 0.045 foot in this well) and short, light trains cause the smallest ones.

In Fort Myers, Fla., where a well 35 feet deep is about 40 feet from the railway, a similar compressional effect has been noted. However, in this case, as soon as the train has departed, the aquifer expands momentarily and a vertical line is made on the chart extending below the line representing the position of the water table before the passage of the train. The resultant mark on the chart is similar to that made by an earthquake, except that it is not as symmetrical—the upper part of the mark (compression) shows a slightly greater range than does the lower part of the mark (expansion). Obviously, the aquifer at Fort Myers is less competent and considerably more elastic than the one at Miami.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
Feb. 24, 1950.

DETAILED SURVEY OF THE CHEMICAL COMPOSITION OF ROCK LAYERS IN AN AGRICULTURAL LIMESTONE QUARRY.

W. D. KELLER, ARNOLD W. KLEMME, AND E.E. PICKETT.

ABSTRACT.

A typical small quarry, producing agricultural limestone (dolomite) from the Jefferson City formation in southwest Missouri, was sampled bed by bed for chemical and spectrographic analyses.

Calcium and magnesium are present as mega constituents, and Mn, Cu, B, Cr, Sr, Ba, Ni, Ag, V, with sporadic Pb and Zn are present as trace elements or potential micronutrients. Variations in composition between adjacent layers are notable.

Brief consideration is given to the role of trace elements as micronutrients, the function of Ca and Mg limestone as a soil amendment, and the desirability of cooperative efforts by pedologists and geologists in the development of agricultural limestone deposits.

INTRODUCTION.

Intelligent prospecting for agricultural limestone quarry sites and quality production from "agstone" (so termed by groups within the industry) quarries now requires the use of considerably more geological and chemical information than has been commonly employed in the past. The older custom was to sell fines and dust (mostly rich in clay and soil residues from incompletely stripped overburden), which unavoidably remained as an undesirable by-product from crushing stone employed for other uses. Now the production of agricultural limestone is profitable in itself. More than 25 million tons of limestone were crushed and sold for agricultural purposes in 1948, and the demand is continuing to rise. The agstone industry needs consideration by economic geologists.

The necessity for technical information on agstone is arising as a result of the currently developing and expanding soil testing programs, which determine the specific needs of soils in particular areas or instances. By means of soil tests, county agricultural agents, supervisors of balanced farming, and soils scientists are prescribing the addition of definite amounts of Ca, of Mg, of certain trace elements, or combinations of them to restore an optimum balance between them in a soil. Hence, to furnish the definite demands of the consumer, the producer of agstone must know what product he has, or what he can make available. The production of agstone must rise to the same technical level as the soil testing.

Serious magnesium deficiencies are being discovered in many soils, and Mg/Ca imbalances are found in others. Dolomites are being searched for now where previously emphasis was put on high calcium stone. Obviously a patch

of locally dolomitized limestone, or a faulted or other structural occurrence of dolomite within a surrounding high calcium area becomes a veritable "little gold mine." Some far seeing and versatile operators are looking for quarry sites where both dolomite and high calcium limestone can be produced at will from a single crusher plant. At the same time the factors of topography, overburden, favorable location to market or transportation facilities, and avoidance of chert or silica sand, which abrade machinery, continue to enter in. Obviously geological considerations are paramount in prospecting for such preferred quarry sites.

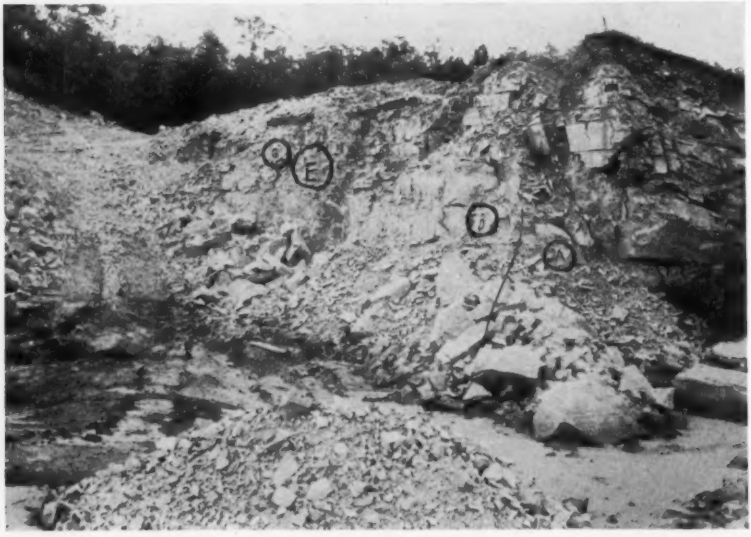

FIG. 1. MFA agricultural limestone quarry near Marshfield, Missouri. The letters on individual beds permit the quarry foreman to correlate the laboratory analyses with rock being quarried. The height of the letters represent the thickness of the layer. Circles inked in on photograph aid in locating the letters.

Trace elements (Mn, Cu, Co, B, Zn, and others) which are known to be absolutely necessary for plant (also animal and human) growth are being lowered to deficiency levels in soils by cropping, leaching, and fixation. Limestones contain tiny amounts of these elements, although in variable quantities, and may replenish the trace elements in more or less adequate quantities through ordinary liming practice. Complete geological information about limestone or other agricultural stone must include an analysis for its trace element content. Hence the need for technical work of an economic geological nature on agricultural limestones pyramids rapidly.

Layer by layer, examination and analyses may be necessary to show what a quarry face or a stratigraphic section will furnish. As an illustration of the

variations which may occur across the face of a single small quarry, and of some of the agricultural-geological considerations which apply, this paper presents a detailed technical study made of a typical small producing agstone quarry in Missouri, which is being operated under ordinary conditions. Emphasis is placed on agricultural considerations.

FIELD EXAMINATION.

The quarry referred to is operated by the MFA[1] (Missouri Farmers Association) near Marshfield, Missouri, about 25 miles northeast of Springfield in the southwestern part of the state. A rock face about 30 feet high reveals the Jefferson City (Ordovician) dolomite on the side of a valley bluff. Information is not available as to the reason for the original location of the quarry at this particular site, but the choice was probably based on physical convenience rather than on the chemical composition of the rock.

To provide a basis of correlation between the individual beds and their chemical compositions, so as to be usable to the quarry foreman after analyses were made, each layer was marked for later reference by painting on it a letter of the alphabet. (Fig. 1.) This procedure has proven to be very practical.

Brief lithologic descriptions of the beds, which are separated by thin partings, are given below:

DESCRIPTION OF EXPOSED BEDS.

Layer		Thickness inches
J.	Tan to brownish, weathered, coarsely crystalline, cherty dolomite. Irregular upper surface due to weathering.	18
I.	Tan, slightly oxidized, coarse dolomite, irregularly laminated.	36
H.	Fine-grained, grayish "cotton rock."	15
G.	Similar to H from which it is separated by a thin parting.	15
F.	Thinly laminated, medium gray, earthy dolomite. Brownish oxidized upper part.	9
E.	Prominent, thick, massive layer of fine-grained dolomite with fucoidal upper surface. Slightly mottled, but having an overall slight bluish cast. The "blue layer" of the quarry men.	36
D.	Earthy, tan-gray, fine-grained dolomite. Upper part is thinly laminated.	6
C.	Massive, gray, fine-grained dolomite. "Cotton rock" variety, slightly more lustrous and compact than the most typical.	40
B.	Similar to C, separated from it by a thin parting.	28
A.	Bed similar to B and C. The same kind of rock is reported by quarry foreman to continue 10–12 feet lower to quarry floor, now covered by broken stone.	120
		Quarry floor

Each bed of rock was carefully sampled by breaking off its fresh surface a series or strip of small chips extending entirely across the bed. They were placed in paper bags and sent to the chemical laboratory for crushing and analysis.

LABORATORY PROCEDURE.

Conventional wet analytical methods for the analysis of agricultural limestone were used to determine the acid (HCl) insoluble content, the $CaCO_3$ equivalent, and the magnesium content.[2]

[1] Permission to visit and report on quarry by courtesy of Dr. Herman Haag, in charge of plant foods, MFA.

[2] These analyses were made in the analytical laboratory of the Department of Agricultural Chemistry, University of Missouri, under the direction of Prof. Chas. W. Gehrke.

CHEMICAL ANALYSES OF THE ROCK LAYERS.

The results of the chemical analyses are grouped in Table I. The acid insoluble and magnesium carbonate contents, and *$CaCO_3$ equivalent* (capacity to neutralize acid) were determined directly; the percent actual $CaCO_3$ was computed by subtracting from 100 percent the sum of the percents $MgCO_3$ and acid insoluble. To economize on the number of lengthy and costly magnesia analyses, composite samples of the lithologically similar layers were run, and no magnesia determinations were made of the impure, earthy layers.

TABLE 1.

ANALYTICAL RESULTS OF MAJOR CONSTITUENTS OF QUARRY LAYERS.

Layer	$CaCO_3$ equiv.	Percent acid insol.	Percent $MgCO_3$	Percent $CaCO_3$
J	69.10	34.49	—	—
I	95.15	10.39	41.84	48
H	84.80	20.20	40.21	40
G	83.90	20.36		
F	72.00	31.63	—	—
E	81.60	22.86	36.28	41
D	67.55	38.77	—	—
C	98.20	7.96	44.48	46
B	95.80	9.98		
A	95.30	10.51		
Gr. qy.	98.95	0.47	0.5 approx.	99

Referring to Table 1, it is apparent that the sequence of layers A, B, and C (and the stone below A if the quarry foreman was correct) is the lowest in acid insoluble impurities in the quarry, and will furnish agstone highest in Ca and Mg. A downslope, or stratigraphically lower location of the quarry which would occupy chiefly the lower part of the section would be preferable. Geological aid in locating the quarry site would have been profitable.

Layers D, F, and J are high in content of clay and chert (acid insoluble impurities). Part of the quarry production is for chats and road rock, and it might pay to segregate, during hand loading of rock lumps, as much of the earthy stone as possible for road rock.

Layer E is higher in acid insoluble impurities than desired but it is also somewhat richer in trace elements than other layers.

It is reassuring to the field geologist to find a close correlation between rock appearance in the field and anticipated analytical results. Earthy-appearing layers ran high in acid insoluble content, and lithologically similar field units gave mutually similar Ca and Mg analytical results. These relationships will facilitate field prospecting.

Data on a sample of high calcium limestone, "Gr. Qy.," have been added for purposes of comparison between calcium limestone and dolomite. Sample "Gr. Qy." was taken from the Burlington (Mississippian) limestone in the J. J. Griesemer quarry located about 3 miles east of Springfield.

Increasing demand, amounting to virtual necessity in some cases, is arising for a report on the actual Ca and Mg in limestone in place of the older

$CaCO_3$ equivalent. The latter merely indicates an equivalency of acid neutralizing capacity, and was adopted by chemists to test the efficacy of limestone when Soils men first thought that acidity in soil was bad, and that the function of limestone added to soil was to neutralize acidity. It is now recognized that the main function of a limestone soil amendment is to furnish Ca and Mg to the soil colloids which in turn pass them on to plants via ion exchange, and that some H^+ ions are desired in most soils. Calcium deficiency in soil was discovered first, but Mg deficiency is now being recognized in various localities. Therefore, the need for definite information on the relative Ca and Mg contents of a limestone is obvious and logical.

To illustrate the inadequacy of a $CaCO_3$ equivalent analysis to describe the composition of a limestone that contains dolomite, three hypothetical limestones, each testing the same 90% $CaCO_3$ equivalent, are listed below with their computed actual compositions. Dolomite has a higher acid neutralizing capacity than calcite because the atomic weight of Mg is only 24.32 as against 40.08 for Ca; pure dolomite has a $CaCO_3$ equivalent of about 108.4 percent. It is obvious from this illustration that a $CaCO_3$ equivalent analysis is not definitive of the composition of the stone.

Three hypothetical limestones, each testing 90% $CaCO_3$ equivalent

	(1)	(2)	(3)
Acid Insol. Imp.	10%	17%	12%
Actual $CaCO_3$	90%	46%	76%
Actual $MgCO_3$		37%	12%

TRACE ELEMENT ANALYSES OF THE ROCK LAYERS.

The rock layers were analyzed individually for their trace element content with a Jarrell-Ash 480 cm adjustable grating spectrograph. The limestone powder (through a 100 mesh screen) was burned in the negative crater of a 10-amp, 110-volt DC graphite arc, the "cathode-layer" method of excitation. The spectra were photographed in the second order between 2400 and 4200 Angstroms (dispersion 3.5 Angstroms/mm) and in the first order between 4000 and 56,000 Angstroms.

The spectrum plates were examined in a projection-comparator where line densities were compared visually with those in a series of spectra of synthetic standards of known composition. The various errors and approximations limit the accuracy of the quantitative estimates to about $\pm$ 50 percent of the amount present.

In Table 2 are assembled the results of the spectrographic analyses. Each element is reported in two ways: the upper figure gives the percent of element present, and the lower figure, the pounds of the element in each ton of limestone. The latter figure is easily converted to parts per million in terms of two million pounds of soil per acre (soil about 6.7 inches thick). Adequate amounts of available trace elements range from a few parts to perhaps 200 parts per million of soil. No generalizations on requirements are possible because a quantity that is so high as to be toxic for one element may be a deficiency level for another.

TABLE 2.

RESULTS OF THE SPECTROGRAPHIC ANALYSES OF THE ROCK LAYERS.

Layer or specimen	Mn	Cu	Co	Zn	B	Ni	V	Mo	Cr	Ag	Sr	Ba	Ti	Sn	Pb
A	5^{-3} 0.1	3^{-3} .0006	—	—	2^{-3} .04	3^{-4} .006	—	—	.01 0.2	5^{-5} .001	.2 4.	.03 0.6	.1 2	—	—
B	2^{-3} .04	5^{-3} .001	—	5^{-3} 0.1	3^{-3} .06	3^{-4} .06	2^{-3} .04	—	.01 0.2	5^{-5} .001	.3 6	.03 0.6	.3 6	—	—
C	5^{-3} 0.1	1^{-4} .002	—	2^{-3} .04	1^{-3} .02	—	—	—	5^{-3} .01	5^{-5} .001	.1 2	.02 0.4	.2 4	—	—
D	.02 0.4	2^{-4} .004	—	3^{-3} .06	5^{-3} 0.1	—	5^{-3} 0.1	—	.02 .4	2^{-5} .0004	.2 4	.2 4	.3 6	—	—
E	.03 .6	5^{-4} .01	—	—	3^{-3} .06	3^{-4} .006	5^{-3} 0.1	—	.03 .6	2^{-5} .0004	.05 1.	.03 0.6	.2 4	—	2^{-4} .004
F	3^{-3} .06	5^{-4} .01	—	.02 0.4	5^{-3} 0.1	5^{-4} .01	3^{-3} .06	—	.03 .6	2^{-5} .0004	.02 0.4	.03 0.6	1.0 20	—	—
G	.01 0.2	5^{-4} .01	—	1^{-3} .02	2^{-3} .04	2^{-4} .004	—	—	.02 .4	2^{-5} .0004	.02 0.4	.03 0.6	.2 4	—	2^{-3} .04
H	.01 0.2	3^{-4} .006	—	1^{-3} .02	1^{-3} .02	2^{-4} .004	1^{-3} .02	—	.02 .4	5^{-5} .001	.03 0.6	.02 0.4	.2 4	—	—
I	3^{-3} .06	5^{-4} .01	—	—	2^{-3} .04	2^{-4} .004	—	2^{-3} .04	5^{-3} .01	—	.05 1	.03 0.6	.1 2	—	1^{-4} .002
J	.02 .4	1^{-3} .02	—	—	3^{-3} .06	5^{-4} .01	1^{-3} .02	3^{-3} .06	.01 0.2	2^{-5} .0004	.3 6	.2 4	.1 2	2^{-4} .004	3^{-4} .006
Bin	1^{-3} .02	2^{-4} .004	—	—	1^{-4} .002	1^{-4} .002	—	—	.02 .4	2^{-5} .0004	.05 1	.03 0.6	.2 4	—	2^{-4} .004
Chats and road rock	3^{-3} .06	1^{-3} .02	—	1^{-2} .02	1^{-3} .02	5^{-4} .01	1^{-3} .02	—	.01 .02	—	.2 4	.2 4	.2 4	—	—
Gr. qy.	.02 0.4	2^{-4} .004	—	—	—	—	—	—	2^{-3} .04	—	.1 2	.02 0.4	.01 0.2	—	—

Amount of each element reported in percent present, upper figure, and in pounds of element per ton of limestone, lower figure. The figures like 5^{-3} are abbreviations of 5×10^{-3}.

Looked for, but not detected in all above samples: Cd, Li, Bi, As, Sb, Be, Ga.

It should be noted that the analyses are in terms of the element, not the carbonate, oxide, or phosphate. Equivalent values in terms of compounds conventionally used on the soil will be higher. For example, one pound of B is present in 8.8 lbs of borax, and one pound of Mn represents 4.15 pounds of 65% $MnSO_4$.

A detailed review of the quantities of trace elements in each individual layer is unnecessary, but in passing it appears that layer E is probably the richest, considering both quantity and variety.

Manganese is present in all layers but highest in layer E. Copper occurs in all layers, as also does boron. Mn, Cu, and B have been found to be ab-

solutely essential in plant nutrition and reproduction (viable seed), and, therefore, their wide occurrence in the limestones is gratifying. Although very little is known definitely about the mineralogy of the trace elements, a few suggestions will be offered. Manganese may occur as the carbonate,[3] or it may be present as tiny particles of the oxide which settled down with the limestone as the latter was deposited. Copper probably occurs as the carbonate, but chalcopyrite is not rare in Missouri limestone, and aurichalcite has been reported.[4] Boron was probably carried down in association with the depositing limestone because boric acid is significantly present in ocean water.[5]

Cobalt was not detected in any of the samples, but the spectrographic sensitivity for Co in a limestone mixture is not very high. Cobalt has been singled out for special mention because it is an essential element in vitamin B_{12}, and because a balanced trio of Mn, Cu, and Co not only increases the effectiveness of the others in nutrition but as a group they apparently catalyze the uptake of other micro and macronutrients. Where needed elements are not present naturally in agstone, it may be desirable to "fortify" the agstone by adding them as mineral concentrates or in crude ores or rock which contains them.[6]

Zinc was found in several layers but it is highest in clayey F. It may possibly occur in the crystal lattice of the clay or it may be present as tiny particles of sphalerite. Small "shows" of pyrite, galena, or sphalerite are not uncommon in the Jefferson City dolomite in southern Missouri, hence the presence of Pb and Zn are to be expected. Indeed, Pb and Zn are detected less commonly and less abundantly in many spectrographic analyses of Missouri limestone collected by the senior author (report in preparation) near the lead and zinc mining districts than might be expected on geologic grounds.

Nickel occurs sparingly in all layers except C and D. Its mineralogy is uncertain, except that millerite has been found in cavities in the Mississippian limestone of eastern Missouri.

Vanadium is relatively high in layers D and E, but occurs in several others. Because this dolomite is clayey, perhaps the V resides in the crystal lattice of the clay as suggested possibly for illite by Hendricks.[7]

Molybdenum, another essential element in plant nutrition, is sparingly present in layers I and J. Plant requirements are usually low for Mo. Its mineralogy here is not known.

Chromium is widespread and fairly abundant in these quarry layers. So far as known, Cr is not essential to plant nutrition.

The writers can only speculate on its mineralogic occurrence—it merits research because of the relative abundance of Cr. It should be noted that Layer E, rich in trace elements, had a mottled and slightly but definitely bluish cast. We now wonder if the trace element content played a part in its color.

[3] Claffy, Esther W., Spectrochemical analysis of rocks and minerals: Am. Jour. Sci., vol. 245, pp. 35–48, 1947.

[4] Keller, W. D., Aurichalcite in Missouri: Am. Mineralogist, vol. 46, pp. 375–376, 1940.

[5] Moberg, E. G., and Harding, M. W., The boron content of sea water: Science, vol. 77, p. 510, 1933.

[6] Keller, W. D., Rock and mineral sources of nutrient trace elements: Pit and Quarry, May 1949.

[7] Fischer, Richard P., Vanadium deposits of Colorado and Utah: U. S. Geol. Survey Bull. 936–P., p. 377, 1942.

Silver occurred sparingly in all layers except I. No need has been established for silver in plant nutrition, but the element has been found to affect intestinal enzymes in human beings.

Barium and strontium are widespread and abundant in limestone, presumably as carbonates.

Tin was detected only in layer J, whereas lead is more common.

Aside from the scientific interest attached to the mineralogy of the trace elements, their combination is of paramount importance in relation to their availability (solubility) to plants. Manganese is readily available to the soil system, via acid clay, from the carbonates but notably less so from the oxides.[8] Boron, if associated with the carbonate minerals might be available, but if locked up in tourmaline would never be released for practical purposes. Tourmaline is not particularly abundant in the insoluble residue of the Jefferson City dolomite and boron has been found in many other limestone samples —hence it is probably available with the carbonate minerals. Probably the copper is in a form which is soluble in oxidizing ground waters simply because copper generally is soluble in surface water.

Although little direct information on the mineralogy of the trace elements has been assembled, it seems logical that they may be present in several forms: (a) they may proxy to a very limited degree for others in crystal lattices, *e.g.*, Mn for Ca in the carbonate, (b) they may be mechanically included as insoluble clastic mineral particles which settled into the limestone during deposition, pyrolusite for example, or (c) they may be present in very tiny crystals as mixtures or replacements, like galena or sphalerite in the limestone. Laboratory determination of the nature of their occurrence does not appear simple because strong mineral acids which dissolve dolomite (to free the trace elements) may also dissolve the minerals containing trace elements, although weaker plant and soil acids may not attack both. Furthermore, trace amounts of proxying elements can hardly be detected by X-ray measurements of crystal unit cells. With present, inadequate means of instrumentation we may need to be satisfied with the somewhat empirical utilitarian technique of Graham and students[9] using acid clay as the reacting and extracting agent. Even this method needs to be correlated with faster working reagents to save time, after standards have been set up.

From the above discussion it becomes apparent that the problems of the most effective development and utilization of agricultural limestone are bilateral —they involve both geology and soil science. Moreover, the factor of economics, for the cost of transporting heavy rock products is high, must be considered with the mineralogy and chemical composition of the stone. The radial distance that one agstone deposit can serve a surrounding area is definitely limited by competitive costs; neither can the quarry site nor the farm with the deficient soil be moved. However, when the value of an agricultural stone is assessed on the basis of its composition, and the needs of the soil in

[8] Konnur, B. B., Weathering of manganiferous minerals by clay colloids: Unpublished Masters thesis, University of Missouri.

[9] Graham, E. R., Primary minerals of the silt fraction as contributors to the exchangeable-base level of acid soils: Soil Science, vol. 49, pp. 277–281, 1940.

terms of its deficiency, the factor of competitive transportation cost may be decidedly modified. It appears that detailed field and laboratory studies will be necessary in order to determine the real value of formations and of particular occurrences of limestone and other potential fertilizer rocks [10] for agricultural purposes. Possibly the approach described in this paper may be useful.

SUMMARY.

The layers of Jefferson City dolomite in a small quarry near Marshfield, Missouri, were examined geologically and sampled systematically for chemical and spectrographic analyses.

Considerable variation in acid insoluble impurities, and consequent Ca and Mg content, occurs between different beds of rock. Information on the mineral and chemical composition of available rock should prove helpful in selecting agricultural limestone quarry sites. Lithologic appearance can commonly be correlated with chemical composition.

Agricultural limestone should be classified on a basis of Ca, Mg, and trace element content rather than on its acid neutralizing, $CaCO_3$ equivalent.

The content of trace elements is variable between beds. Mn, Cu, B, Sr, Ba, and Cr are common, and Ni, V, Ag, Ga, Pb, and Zn are less common or less abundant.

The most efficient development and utilization of agricultural stone calls for close cooperation between pedologists who discover their soil needs; and geologists who discover what the rocks and minerals can supply.

DEPARTMENTS OF GEOLOGY, SOILS, AND AGRICULTURAL CHEMISTRY,
UNIVERSITY OF MISSOURI,
COLUMBIA, MO.,
Feb. 8, 1950.

[10] Keller, W. D., Native rocks and minerals as fertilizers: Sci. Monthly, vol. 66, pp. 122–130, 1948.

VALUE OF DOMESTIC PRODUCTION OF MINERALS FROM VARIOUS CLASSES OF ROCK.[1]

V. E. McKELVEY, J. E. CRAWFORD, D. F. DAVIDSON, AND R. L. BOARDMAN.

ABSTRACT.

Fluids and sedimentary rocks accounted for 48 and 36 percent, respectively, of the total value of the 1946 domestic mineral production. The epigenetic (vein and replacement) and metamorphic deposits each contributed 6 percent of the total, and residual and igneous deposits accounted for 3 and 1 percent, respectively. Fuels were the most valuable of all the minerals produced—77 percent of the total. Petroleum, natural gas, and similar fluid fuels accounted for 47 percent of the total production and 98 percent of that from fluids; bituminous coal made up 24 percent of the total production and 67 percent of that from sedimentary rocks; anthracite coal was valued at 6 percent of the total production and 92 percent of that from metamorphic rocks. Exclusive of fuels, the bulk of the production of nonmetallics, and of the total mineral production too, was from sedimentary rocks (74 and 50 percent, respectively) and from veins and replacements (8 and 28 percent, respectively). Most of the production of metals, however, was from veins, etc. (62 percent) and residuum (29 percent).

INTRODUCTION.

REFERENCES are frequently made in textbooks to the relative value of the minerals produced from various rock types, but, as far as we are aware, the only quantitative statement of these values is the brief summary published in 1931 by Brinkman.[2] In the course of a discussion regarding the relative importance of the field of sedimentary economic geology,[3] it was found desirable to compare the value of the minerals produced from sedimentary rocks with that from other rock types, and we therefore classified and tabulated the mineral production of 1946. This tabulation we present here in full in the hope that it may be of general interest.

The 1946 production figures [4] were chosen for this study, not only because they are the latest available but also because they appear to be representative (at least as regards the relative importance of metals and nonmetals) of normal, peacetime production, such as that of the middle 1920's or late 1930's, when the production of metals, fuels and other nonmetals was about 20, 65, and 15 percent, respectively, of the total production.

[1] Published by permission of the Director, U. S. Geological Survey.

[2] Brinkman, R., Über die Verteilung der nutzbaren Elemente auf die Hauptlagerstättengrupen: Zeitschr. prakt. Geologie, vol. 7, pp. 97–105, 1931.

[3] McKelvey, V. E., The field of economic geology of sedimentary mineral deposits: *in* Trask, P. D., and others, Applied Sedimentation, pp. 485–505, John Wiley and Sons, New York, 1950.

[4] Matthews, A. F., and others, Minerals Yearbook, 1946: U. S. Bureau of Mines, 1948.

CLASSIFICATION OF MINERAL DEPOSITS.

None of the classifications of mineral deposits [5] have a place for all of the earth materials actually produced. Oil, gas, air (from which oxygen, carbon dioxide, and synthetic nitrogen are produced), brines, and sea water, for example, are not included in most classifications, yet they are mineral deposits in a very real sense.[6] Perhaps they are not considered because we are accustomed to think of a mineral in the strict sense of being an inorganic, natural solid. Yet water is also defined as a mineral [7] and few would deny the propriety of including at least oil, natural gas, and brines in a statement of the mineral production or mineral resources of a given area.

We also generally think of rocks as being divided into three groups—igneous, sedimentary, and metamorphic—but it has long been recognized that other earth materials, such as residual and supergene ores, talus, landslides, veins, and water, are separate rock types that do not belong to the three main groups.[8] These materials are much smaller in volume than those of the three principal rock types but some of them are of equal if not greater importance economically. They therefore deserve recognition as separate rock types in any classification of mineral deposits.

For the purpose of tabulating mineral production according to rock type we have therefore extended the traditional classification to include three additional rock types—residuum, veins and replacements, and fluids. This classification has some disadvantages; whereas some of the groups are defined genetically, others (veins, etc., and fluids) are defined descriptively. But each of the groups does have certain structural, textural, or compositional characteristics that serve to distinguish most of its rocks from those of other groups.

These distinguishing characteristics are not always sharp, however, and it is difficult to classify some mineral deposits in terms of the six rock types of the classification used here or, for that matter, in terms of any other classification. Those most difficult to classify are certain types of igneous, metamorphic, and vein deposits. Pegmatites, for example, resemble some veins more than they do igneous rocks and, in fact, some investigators believe that they are veins. Some minerals found in contact metamorphic rocks have been derived from the igneous intrusions that produced the metamorphism and might be classed as igneous, metamorphic, or vein deposits. Somewhat arbitrarily perhaps, we have classed pegmatite deposits as igneous and most other epigenetic deposits as veins and replacements. We have included with the metamorphic rocks only those deposits, such as marble, metaquartzite, slate, and kyanite, that have been altered largely by recrystallization of materials within the primary rock and not by the addition of materials.

Many mineral deposits have been acted upon by more than one process and

[5] The various classifications of mineral deposits are well summarized by Alan M. Bateman, Economic Mineral Deposits, pp. 365–374, John Wiley and Sons, New York, 1942.

[6] Armstrong, E. F., and Miall, L. M., Raw materials from the sea: Constructive Publications Ltd., Leicester, England, 1946.

[7] Palache, C., Berman, H., and Frondel, C., Dana's System of Mineralogy, p. 494, John Wiley and Sons, New York, 1946.

[8] Ashley, G. H., et al., Classification and nomenclature of rock units: Geol. Soc. America Bull., vol. 44, pp. 423–459, 1933.

might properly be classed as one of two or more different rock types. The Lake Superior iron ores, for example, are generally believed to be residual concentrations of syngenetic sedimentary deposits. The structural relations of the sandstone vanadium ores of the Colorado plateau show them to be epigenetic but their stratigraphic relations suggest that they may be reconstituted sedimentary deposits. Deposits of such dual origin have been classified according to the process that made the material of commercial value. The Lake Superior ores are thus classed as residual and the sandstone ores as vein. Similarly, anthracite coal is classed as metamorphic. Other types of coal, incidentally,

TABLE 1.

SUMMARY OF 1946 DOMESTIC MINERAL PRODUCTION, INCLUDING FUELS, CLASSIFIED BY ROCK TYPE.[1]

Rock Type	Metals		Nonmetals		Total	
	Value	Percent of total metals	Value	Percent of total nonmetals	Value	Percent of grand total
Igneous	$ 1,540	0.2	$ 56,300	0.8	$ 57,800	0.8
Sedimentary	47,800	7.4	2,640,000	38.6	2,690,000	35.9
Metamorphic	—		447,000	6.5	447,000	6.0
Veins, disseminations and replacement bodies	402,000	62.3	90,900	1.3	493,000	6.6
Residuum	190,000	29.5	28,100	0.4	218,000	2.9
Fluids	3,650	0.6	3,590,000	52.4	3,590,000	47.8
Totals	$645,000	100.0	$6,850,000	100.0	$7,500,000	100.0

[1] All values are rounded off to three significant figures and are expressed in thousands (000, omitted).

as well as many other sedimentary rocks, are of value because they have been affected by diagenetic processes that differ only in degree of intensity from those generally recognized as metamorphic. As is customary, these changes are not considered sufficient basis for classifying the rocks affected as metamorphic and they are here included with other sediments.

MINERAL OUTPUT FROM VARIOUS ROCK TYPES.

The results of the compilation are summarized in Tables 1 and 2 and the tabulation itself is shown in Table 3. Although, as far as known, the following minerals were not produced domestically in 1946 from deposits of the rock type specified, they were produced from foreign sources from these rock types, or in previous years from domestic deposits:

Igneous—iron, platinum, tin, uranium and radium, nepheline syenite (ceramic), gemstones (beryl, chrysoberyl, diamond, feldspar stones, jade, peridot and chrysotile, ruby, sapphire, spodumene stones, topaz, tourmaline, quartz stones, zircon), phosphate, and quartz crystal.

Sedimentary—chromite, columbium and tantalum, copper, gallium and germanium (recovered from coal), magnetite, lead, magnesium, manganese, tin, uranium, radium, corundum, emery, gemstones (amber, beryl, chrysoberyl, diamond, opal, ruby, sapphire, spinel, spodumene stones, topaz, tourmaline, zircon), and monazite.

Metamorphic—gem garnet, lazurite, spinel, andalusite, dumortierite, and wollastonite.

Veins, etc.—tin, uranium, radium, agate, emerald, lazurite, ruby, sapphire, quartz stones, iodine, sodium nitrate, phosphate.

Residuum—cobalt, gold, nickel, tin, zinc, cornwall stone (kaolinized granite), gemstones (such as beryl, diamonds, and opal) and kyanite.

Fluids—mercury, nickel, and vanadium (all recovered from oil).

TABLE 2.

SUMMARY OF 1946 DOMESTIC MINERAL PRODUCTION, EXCLUSIVE OF FUELS, CLASSIFIED BY ROCK TYPE.[1]

Rock Type	Metals		Nonmetals		Total Metals and Nonmetals	
	Value	Percent of total metals	Value	Percent of total nonmetals	Value	Percent of grand total
Igneous	$ 1,540	0.2	$ 56,300	5.0	$ 57,800	3.3
Sedimentary	47,800	7.4	834,000	74.2	882,000	49.8
Metamorphic	—	—	34,000	3.0	34,000	1.9
Veins, etc.	402,000	62.3	86,700	7.7	489,000	27.6
Residuum	190,000	29.5	28,100	2.5	218,000	12.3
Fluids	3,650	0.6	86,000	7.6	89,700	5.1
Totals	$645,000	100.0	$1,130,000	100.0	$1,770,000	100.0

[1] All values are rounded off to three significant figures, and are expressed in thousands (000, omitted).

Surface and ground waters—our greatest natural resources and the most important produced in both tonnage and value—are omitted from the tabulation only because the amount produced is unknown.

The values for the individual minerals and rocks are not strictly comparable and some are approximations only. As explained in the Statistical Summary of Mineral Production in the U. S. Bureau of Mines Minerals Yearbook,[9] from which the data have been compiled, some production figures represent the value of the crude materials, such as iron ore; some are reported only for refined materials, such as cobalt, germanium and selenium; and some are reported only for the finished product, such as cement. In this compilation, the production figures totaled are of the crude material or the crudest form of the product for which figures are available.[10] As many minerals are mined from more than one type of rock, it is difficult to tell from the general production

[9] Matthews, A. F., and others, op. cit.

[10] The total stated in the tables here, therefore, differs from that published by the Bureau of Mines ($8,859,000,000) because the Bureau of Mines figure includes the value of pig iron rather than iron ore; aluminum ingot rather than bauxite; clay products rather than clay, etc.

figures available how much of the production of a given mineral comes from rocks of one class and how much from another. Moreover, as already emphasized, the uncertain nature of many deposits makes their classification difficult. Inasmuch as the production data are given for all minerals the reader can re-

TABLE 3.

VALUE OF 1946 DOMESTIC MINERAL PRODUCTION, CLASSIFIED BY ROCK TYPE.

Explanation of symbols and figures.

All figures, except those in footnotes, are stated in thousands of dollars.

? Distribution of value by rock type uncertain; may include production from another rock type.

?? No production figures available; value estimated, if stated.

	Rock type					
	Igneous	Sedimentary	Metamorphic	Veins, disseminations, and replacement bodies	Residuum	Fluids
Metallic minerals						
Antimony (ore and concentrates)				798		
Bauxite (ore)		6,000 ?			710 ?	
Beryllium concentrates	18					
Bismuth (metal)				a		
Cadmium metal and compounds				6,360		
Chromite (ore)	105					
Cobalt (metal)				a		
Columbium and tantalum concentrates	9					
Copper (metal)				173,000		
Gallium				a		
Germanium				a		
Gold (metal)		20,700		30,500		
Indium (metal)				17		
Iron (ore)		15,600		13,100	186,000	
Iron, manganiferous (ore)					3,130	
Lead (metal)				49,300		
Magnesium (metal)						3,650
Manganese (ore)				4,770	45 ?	
Mercury (metal)		2 ??		2,490		
Molybdenum (metal)				11,200		
Nickel (metal)				a		
Platinum metals (refined)		1,700 ?		100 ?		
Selenium				a		
Silver		63		18,400		
Tellurium				a		
Thallium				a		
Titanium concentrates	1,410 ?	2,890 ?		1,410 ?		
Tungsten concentrates		280 ?		6,000 ?		
Uranium and radium				??		
Vanadium		100 ?		610 ?		
Zinc				81,700		
Zirconium		500 ??				
Total metals	1,540	47,800		402,000	190,000	3,650

TABLE 3—*Continued.*

	Rock type					
	Igneous	Sedimentary	Metamorphic	Veins, disseminations, and replacement bodies	Residuum	Fluids
Non-metallic minerals						
Abrasives						
Diatomite		b				
Emery				62		
Garnet		75 ??	570			
Grinding pebbles		60 ?				
Artificially rounded granite and quartzite	21 ?		21 ?			
Grindstones		501				
Ground sand and sandstone		4,130				
Millstones, burrstones, chaser stones	5 ?	10 ?				
Pulpstones		4				
Pumice	765 ?					
Pumicite		821 ?				
Quartz (crude, crushed and ground)	150 ?		144 ?			
Rottenstone		16				
Sharpening stones		b				
Tube mill liners	14 ?		30 ?			
Tripoli					533	
Arsenic				678		
Asbestos			505 ?			
Asphalt and related bitumins						
Bituminous rock				2,860		
Gilsonite				1,400		
Wurtzilite				1		
Barite				1,980	3,260	
Cement (Raw materials include cement rock, limestone, oyster-shells, marl, clay and shale, gypsum, sand, iron ore, pyrite, and a host of miscellaneous materials)						
Natural, Puzzolan		4,160 ?				
Portland		292,000 ?				
Clay						
Ball clay		2,400				
Bentonite		4,360				
Fire clay		15,800 ?			5,000 ?	
Fullers earth		3,700				
Kaolin		12,000 ?			1,550 ?	
Miscellaneous (including slip clay)		10,000 ?			6,000 ?	
Coal						
Bituminous and lignite (includes anthracite mined elsewhere than Pennsylvania)		1,810,000 ?				
Anthracite (Pennsylvania)			413,000			

TABLE 3—*Continued.*

	Rock type					
	Igneous	Sedimentary	Metamorphic	Veins, disseminations, and replacement bodies	Residuum	Fluids
Non-metallic minerals(*cont.*)						
Feldspar	2,590					
Aplite	c					
Fluorspar and cryolite				9,040		
Gemstones						
Agate		b				
Jade		d				
Turquoise				d		
Gypsum (crude)		12,400				
Helium						479
Lime (quick and hydrated lime)		40,600				
Dolomitic lime		10,400				
Limestone (agricultural)		32,500				
Oystershells		357				
Calcareous marl		248				
Magnesium compounds and miscellaneous salines						
Magnesia—caustic calcined and refractory		1,000 ?		5,190 ?		3,730
Specified magnesias and magnesium hydroxide						1,220
Precipitated magnesium carbonate						876
Magnesium chloride						??
Magnesium sulphate						??
Calcium and calcium-magnesium chloride						2,280 ?
Bromine and bromides						8,560
Iodine						e
Sodium carbonate		1,000 ?				2,430 ?
Sodium sulfate		500 ?				1,200 ?
Borates		9,580				
Mica						
Sheet	218					
Scrap	1,040 ?					
Mineral waters						e
Natural gas						885,000
Natural gasoline and liquified petroleum gases						179,000
Nitrogen compounds						
Anhydrous ammonia (synthetic)						??
Ammonium sulfate (synthetic)						18,000
Sodium nitrate (synthetic)						??
Peat		1,010				
Petroleum (crude)						2,442,000
Phosphate rock		23,300			7,780	
Potash		27,200 ?		100 ?		4,900 ?
Salt		13,300 ?				31,600 ?

TABLE 3—*Continued.*

	Rock type					
	Igneous	Sedimentary	Metamorphic	Veins, disseminations, and replacement bodies	Residuum	Fluids
Non-metallic minerals(*cont.*)						
Sand and gravel						
Gravel, building		34,400				
paving		54,300				
railroad		6,340				
miscellaneous		1,440				
Sand, building		32,000				
engine		1,920				
filter		285				
fire or furnace		334				
glass		9,540				
grinding, polishing and sand blast		1,380				
molding		9,530				
paving		18,000				
railroad ballast		262				
other		1,750				
Slate			8,840			
Stone						
Dimension stone (building stone, curbing and flagging)						
Basalt and trap rock	70					
Granite	16,700					
Limestone		5,880	7,080			
Sandstone		2,330				
Miscellaneous			902 ?			
Crushed and broken stone						
Basalt						
Rip rap	1,110					
Concrete and road metal	16,100					
Railroad ballast	2,430					
Other uses	970					
Granite						
Rip rap	714					
Concrete and road metal	8,460					
Railroad ballast	2,400					
Other uses	1,200					
Limestone						
Rip rap		2,050				
Fluxing stone		20,800				
Concrete and road metal		66,300				
Railroad ballast		6,080				
Other uses		22,100				
Marble			839			
Sandstone						
Rip rap		654				
Concrete and road metal		1,830				
Railroad ballast		315				
Refractory		2,950 ?				
Other uses		3,330				

TABLE 3.—*Continued.*

	Rock type					
	Igneous	Sedimentary	Metamorphic	Veins, disseminations, and replacement bodies	Residuum	Fluids
Non-metallic minerals(*cont.*)						
Miscellaneous			8,280			
Dolomite						
Basic magnesium carbonate		465				
Refractory uses		1,150				
Sulfur and pyrites						
Native sulfur				66,100		
Pyrite		5 ??		3,220		
Talc, ground soapstone and pyrophyllite			6,440			
Minor non-metals						
Graphite			253			
Glauconite		425				
Kyanite			d			
Lithium compounds	152 ?					152 ?
Mineral pigments					4,000 ?	
Olivine	93					
Perlite	23					
Strontium minerals (celestite)		4				
Topaz (industrial)	c					
Vermiculite	868					
Total non-metals	56,300	2,640,000	447,000	90,900	28,123	3,590,000
Total metals and non-metals	57,800	2,690,000	447,000	493,000	218,000	3,590,000

a. The total production of bismuth, cobalt, gallium, germanium, nickel, selenium, tellurium, and thallium was valued at $2,730,000.

b. The total production of sharpening stones, gem agate, and diatomite was valued at about $4,870,000.

c. The total production of aplite and industrial topaz was valued at $240,000.

d. The total production of jade, turquoise, and kyanite was valued at about $900,000. This amount is arbitrarily divided equally among sedimentary, metamorphic, and veins, etc., in the totals.

e. The total production of iodine and mineral waters was valued at about $3,800,000.

classify specific deposits and revise the totals as he sees fit. We believe, however, that only two minerals of questionable classification—Lake Superior iron ore and anthracite coal—have a value large enough to change the distribution of the total production by as much as one percent.

CONCLUSIONS.

Fluids and sedimentary rocks accounted for the greatest part of the total 1946 domestic mineral production—48 percent and 36 percent respectively. The epigenetic (vein and replacement) and metamorphic deposits each contributed 6 percent of the total, and residual and igneous deposits accounted for the least part of the total production—3 and 1 percent respectively.

Fuels, of course, were the most valuable of all the minerals produced—77 percent of the total 1946 production. Petroleum, natural gas, and similar fluid fuels accounted for 47 percent of the total production and 98 percent of that from fluids; bituminous coal made up 24 percent of the total production and 67 percent of that from sedimentary rocks; anthracite coal was valued at 6 percent of the total production and 92 percent of that from metamorphic rocks. Exclusive of fuels, the bulk of the production of nonmetals, and of the total mineral production as well, was from sedimentary rocks (74 and 50 percent, respectively) and from veins and replacements (8 and 28 percent, respectively). Most of the production of metals, however, was from veins, etc. (62 percent) and residuum (29 percent).

ACKNOWLEDGMENTS.

We gratefully acknowledge the cooperation received from Mr. Allan F. Matthews, Editor of the U. S. Bureau of Mines Minerals Yearbook. Although we assume full responsibility for any errors that the tabulation may contain, Mr. Matthews kindly checked parts of it and in addition supplied the total value of several groups of minerals whose individual production values are confidential. Mr. S. G. Lasky and Mr. H. G. Ferguson of the U. S. Geological Survey criticized the manuscript and made several valuable suggestions.

U. S. GEOLOGICAL SURVEY,
WASHINGTON 25, D. C.,
March 13, 1950.

SCIENTIFIC COMMUNICATIONS

A SUMMARY OF HORIKOSHI'S STRUCTURE OF CUPRIFEROUS PYRITE DEPOSITS IN SCHIST.[1]

FOREWORD.

Inasmuch as Horikoshi's paper on the Besshi type of ore deposit appears to be the best of its kind on the most productive type of Japanese copper deposit, the publication of a summary in English seems desirable. The original contains numerous mine descriptions and diagrams graphically illustrating the conclusions presented in this summary. The complete original text was published in the Japanese language by the Japanese Institute for the Advancement of Science, December 1940, under the title "Besshigata Kosho no Keitai-teki Keuky," literally translated as "Morphological Studies of the Besshi Type of Ore Deposit," by Yoshikazu Horikoshi. This summary is based on a preliminary translation by M. Miura, Translation Branch, Natural Resources Section. The complete translation is in the files of the Natural Resources Section,[2] in Tokyo. Page numbers and headings from the original text are presented below to indicate the relative amounts of material in the complete version.

OUTLINE OF THE ORIGINAL PAPER.

1. Introduction 1
   Principal mines investigated 1
   Kune, Minenosawa, Iimori, Higashiyama, Kotsu, Miyoshi, Minawa, Sazare, Shirataki, Iyo, Besshi, Ehime, Nii, Kamegamori, Nishinokawa, Tihara, Izushi, Imade, and Makimine in Japan Proper, and Domon and Namakoyama in Formosa.
2. Location of ore deposits 2
   Chlorite schist and piedmontite schist 3
   Chlorite schist 3
   Piedmontite schist 4
   Localization of ore 5
3. Form of the ore deposits 7
   General 7
   Ore shoots 8
   Mine descriptions 9
   Relation of ore shoots and folding 19
   Branching 20
4. References 22, 23

HOST ROCKS.

Schist or phyllite is the host rock for the cupriferous pyrite deposits of the 21 mines studied. No particular type of schist constitutes the sole host rock, but green-colored schist is the most common. At more than half the deposits, piedmontite [3] schist or some other hard rock, such as quartz schist, hematite

[1] Published by permission of the Director, U. S. Geological Survey.

[2] General Headquarters, Supreme Commander for the Allied Powers, Japan.

[3] The manganiferous epidote, $HCa_2(Al,Mn)_2Si_3O_{13}$, called piedmontite is generally a minor constituent of a glaucophane schist, yet its distinctive red crystals give piedmontite such prominence that the rock containing it is colloquially called "spotted schist."

schist, or quartzite, forms either the hanging wall or footwall. Piedmontite schist is found only in regions of advanced metamorphism; the equivalent rock in less metamorphosed regions is hematite schist or red quartz schist. At three mines the rock on one wall is graphitic phyllite, or graphitic schist.

The principal constituent of most of the green schist is amphibole, and the chief accessory mineral is chlorite. However, close to the ore bodies the situation is reversed, the rock being chlorite schist. This change is recognizable by the character of the rock, its softness and its darker green, more lustrous color. In the light of present knowledge, chlorite schist is an infallible indicator of the proximity of ore.

FORM OF DEPOSITS.

Many of the ore [4] deposits are tabular and have been called bedded veins, but rarely are they strictly conformable with the bedding or schistosity over any considerable distance. However, their near-conformity to adjacent stratification is a notable feature, even for the lenticular bodies.

Branching on a small scale is common, despite the general conformance with the bedding. The most common occurrence of branching is at the ends of the ore bodies. Some deposits have branches where some other structural feature intersects the ore body.

A critical feature is that, without exception, the ore bodies have a direction of elongation parallel to the orientation of the elongate minerals in the wall rocks. Such orientation is observable on the planes of schistosity, and it is of great value in predicting the direction of plunge of ore shoots. This direction also coincides with the axis of folding.

LOCALIZATION OF ORE DEPOSITS.

Most ore deposits of this type are in fissures or shear zones in green schist. The remainder are at the contact of hard and soft rocks. The relationship between folds, rocks, and the thickness of ore is a problem for which a working hypothesis has been developed. Ore is often found at the contact of hard and soft rocks in folded areas, but not so frequently as might be wished. If the soft rock is on the interior side of the folded contact, thick ore can be expected; if the soft rock is on the exterior side of the contact, little or no ore is to be expected. In the former case, the weak rocks crumpled, making suitable channels and voids for ore bodies; in the latter case, the weak rocks stretched tight, choking off any ingress of solutions.

JOHN J. COLLINS.[5]

U. S. GEOLOGICAL SURVEY,
WASHINGTON 25, D. C.,
March 22, 1950.

[4] These massive, pyritic replacements of schist are a world-wide type that have been classified by Lindgren as mesothermal deposits. The minerals in the general order of their abundance are: pyrite, pyrrhotite, chalcopyrite, magnetite, and sphalerite with various amounts of the gangue minerals quartz and calcite. Most of the individual ore bodies are less than a few hundred thousand tons in size, but the ore bodies commonly occur in groups. The largest single ore body in Japan is the Besshi, which has produced 19,000,000 metric tons averaging 3.8 percent copper. Minable ore has ranged from 1 percent to 10 percent copper in this type of deposit in modern times. Gold and silver content has generally been worth less than a dollar per ton.

[5] Geologist, U. S. Geological Survey, formerly assigned to the Natural Resources Section, General Headquarters, Supreme Commander for the Allied Powers, Japan, by arrangement with the Office of the Chief of Engineers, U. S. Army.

DISCUSSIONS

MINING GEOLOGY: A SCIENCE.

ABSTRACT.

Mining geology has recently been described as a branch of engineering, using in part the "laws" of geology. In contrast to that viewpoint, the present writer holds that the chief value of a mining geologist derives from his use of the best possible geological procedures, whatever the problem. In fact certain aspects of mining geology are properly called research.

The recognition of the research aspect and the opportunity to pursue it along with the usual service jobs in mining will attract more good men to the field. This is a challenge to the teacher who wants to place his students and to the company that wants to find more ore.

Sir: In a recent talk and article Forrester (1)[1] expresses a viewpoint on the practice of mining geology that is common, especially among mining engineers and operators: briefly, that a mining geologist is essentially a service engineer. Fortunately this viewpoint is not common among well known mining geologists, nor is it universal among operators.

Perhaps the publication of Broderick's thoughtful and temperate address (2) and of McKinstry's excellent book (3) are sufficient rebuttal. But since Forrester's paper will be read by many students as well as geologists, I am impelled to record specific disagreement, in the hope of counteracting some of the effect of the attitude expressed in his paper. This attitude is especially damaging to the attempt to attract good geologists to mining in competition with Survey work or teaching, and also to the attempt to persuade management to use mining geologists as geologists, rather than merely as technicians.

More positively, I shall insist that under suitable conditions mining geology is much more than routine engineering service, and in fact may offer opportunities for real research.

WHAT IS A MINING GEOLOGIST?

Forrester says "Mining geologists have been practising engineering in the exploration for mineral deposits for over fifty years in much the same manner as they do today." This seems to be agreed. Let us go farther and say "Mining geologists have been practising the geology of mineral deposits for over thirty years in much the same manner as they do today."[2] Is this true? If even partly true, does it suggest that we are in fact treating the geology of mineral deposits as *a science* or as *a technical aspect of engineering?* Is our treatment fruitful or sterile?

[1] Numbers in parentheses refer to bibliography at end of discussion.
[2] The first edition of Lindgren's "Mineral Deposits" appeared in 1913.

Now whatever the reaction to these rather leading questions may be, note that Forrester explicitly concludes that "mining geology is a specific area of engineering built upon a knowledge of certain basic and special sciences." He reaches this conclusion after a short discussion that can be simplified as follows: mining geology is based on

1. "A scientific knowledge of the natural laws" of mineral deposits.
2. Knowledge of various techniques: surveying, geologic mapping, ore estimation, geophysics, and geochemistry, and expression by word, diagram, and map.
3. Knowledge of various tools: the drill, geophysical, and geochemical apparatus.
4. Knowledge of mining methods.

In the course of a rather obscure syllogism, Forrester defines science as "knowledge reduced to law" and "expertness resulting from knowledge." I am sure this made scientists at least as far back as Lyell and Darwin turn over in their graves.

Of course many men trained as mining geologists are spending all their time in surveying, sampling, estimation, and shiftbossing. If this is all they do, they really do not need training in more than elementary geology. Furthermore, any geologist connected with mining obviously must know something of the techniques and tools, including those of mining. In some small mines a man must be geologist, engineer, surveyor, public relations, and several other things at the same time.

But it would be fruitless to continue discussion of Forrester's paper. As a practising exploration geologist I am impelled to disagree with his whole viewpoint, which seems to be that a mining geologist is an engineer using geological principles where needed, or perhaps only whenever he has time.

MINING GEOLOGY VS. GOOD GEOLOGY.

The following statements are, I think, practically truisms and abundantly proved by experience: Only a man with a good geological background can do good geological mapping. Only that man can properly interpret and use the results of geophysics and geochemistry. But even that man cannot do those jobs well when they are entirely subordinate to surveying, mine layout, and other responsibilities. To buttress those statements here are some remarks of wellknown mining geologists, all quoted from the Lindgren Volume (4).

D. H. McLaughlin: "The recognition of significant problems still to be solved and the organization of systematic research to determine the critical facts are essential parts of the geological work (at the Homestake mine). Even though the competition of more urgent duties may be sharp, it is recognized that a fair amount of time must be devoted to the larger geological considerations to stimulate keen, active thinking without which staff work tends to degenerate into routine, geometrical projection, or to merely standardized repetition of accepted ideas." (*i.e.*, according to Forrester, the "scientific knowledge of the natural laws").

F. A. Linforth: "The work of the combined geological, engineering, and sampling departments at Butte is largely a work of service, and great stress is laid on the part of the geologist in aiding actual mining operations. At the same time the fundamental purpose of the geological study is to gain the broadest possible knowledge of the geology of the Butte district."

Paul Billingsley: "No one of us at Tintic has ever yet been able to reach a final correct geological understanding of a mine or an area upon the basis of a single examination, no matter how painstaking the mapping.—The most essential element in a geological organization is the realization that modification of hypotheses is inevitable."

D. H. McLaughlin and Reno Sales: "It is the duty of the mining geologist to be familiar with current achievements and to contribute his share toward them, as well as to make practical use of the results."

Now the common denominator of these quotations and of many others that could be given is clearly that *the fundamental job of a mining geologist is to use the best possible geological procedures.* These include gathering "the broadest possible knowledge of the geology" and the "realization that modification of hypotheses is inevitable," which together, you will note, constitute the scientific method (5, 6).

Are these ideas compatible with the attitude that "science is knowledge reduced to law and embodied in system"? (1, p. 546). Aristotelian learning needed no more than this definition to sterilize objective thought for some 500 years.

WHERE DO WE GO FROM HERE?

The point I want to make is this: *our knowledge of the geology of mineral deposits is woefully small; it must be enlarged.* Try to apply the "law" that mineral deposits are genetically related to the nearest igneous rock! Well, geologists hope to learn more, or else they are not scientists. *Who* is going to learn more? Workers in the Geophysical Laboratory? College professors, who spend much of their time teaching the little that is known and the much that is not? The Geological Surveys? Must we exclude the men who are using geological techniques and hypotheses and finding out daily, if they are scientific observers, whether these work or not?

During one of the Conferences on Training in Geology a speaker (7) separated "research men on the geologic frontiers" from the "great host of their fellows who handle the time-tested tools of the profession." Now this sounds like a reasonable remark, for undoubtedly a separation of some sort does exist. But I suggest that this is the heart of our difficulty; most of our tools are time-petrified, not time-tested.

I would like to get that speaker (a college teacher) into the situation of recommending the spending of money to test his geologic theories, which he has fashioned with the time-tested tools. I think he would be conscious of being on the geologic frontier; in fact it might feel just like the firing line with no foxhole handy. At any rate that feeling is commonly experienced by many exploration and mine geologists.

It seems obvious that the answer to the question "who is going to learn more about mineral deposits" is that no one group has a monopoly on research, because research is going on in all groups. As Rhoades said, "Any geological work related to an engineering undertaking, if it contributes to a better understanding of the field, can be considered research" (8). Likewise the application and testing of "time-tested" hypotheses in a specific mine or area by company geologists can be considered research, when it is realized that rigorous observation is essential and that modification of hypotheses is inevitable.

SUMMARY.

The general conclusions of this paper can be summarized in several comments.

1. Regarding the title of this paper: mining geology *can* be a science, and many examples of scientific work by mining geologists can be found in the literature.

2. Regarding teaching: it seems obvious that mining geology will attract more good men when these men realize that important and sometimes exciting research can be carried on within the framework of commercial geology. Contrast this statement with the offer to allow geologists to be mining technicians and to apply the "laws" of geology!

3. Regarding material rewards: the conditions of employment in company work often have an adverse effect, as pointed out by Broderick and others. The lack of material incentive and the lack of scientific background may well result in selective mediocrity for the profession.

4. Regarding general policy: it seems obvious that mining geology will make further advances as a science chiefly to the extent that mining geologists sell themselves on their value—present and prospective—as geologists, not as technicians. As Broderick says, "we must accept it as a probability that the difficulty of finding mines will outstrip any expectable development of skill in exploring." The mining industry has a large stake in the necessity of finding mines; how many more will be found with the methods of the past fifty years?

E. P. KAISER.

NEW JERSEY ZINC EXPLORATION COMPANY,
SPOKANE, WASHINGTON,
January 12, 1950.

BIBLIOGRAPHY.

1. Forrester, J. D., Mining geology and the engineering aspects of mineral exploration: ECON. GEOL., vol. 44, pp. 545–550, 1949.
2. Broderick, T. M., Exploration for ore deposits: ECON. GEOL., vol. 44, pp. 357–375, 1949.
3. McKinstry, H. E., Mining Geology, Prentice-Hall, New York, 1948.
4. Ore Deposits of the Western States, Am. Inst. Min. Met. Eng., New York, 1933.
5. Conant, J. B., On Understanding Science, Yale University Press, 1947.
6. Chamberlin, T. C., The method of multiple working hypotheses: Jour. Geology, vol. 39, pp. 155–165, 1931.
7. Conference on training in geology: Geol. Soc. America Interim Proc., Part 1, p. 71, 1947.
8. Rhoades, Roger, et al., *in* Report of committee on research in engineering geology, Society of Economic Geologists: ECON. GEOL., vol. 43, p. 314, 1948.

REVIEWS

Structural Petrology of Deformed Rocks, 2nd Edit. By HAROLD W. FAIRBAIRN AND FELIX CHAYES. Pp. 344; numerous figures and tables. Addison-Wesley Press, Inc., Cambridge, Mass., 1949. Price, $12.50.

This is a 2nd edition, according to the preface, of the book that appeared in 1942, although not so stated on the fly-leaf. Dr. Chayes' contribution is two chapters on statistical methods applied to petrofabric data.

The present edition is largely a reference book although, like its predecessor, it has to be read in sequence and not at random. It incorporates the important matter of the many papers that have appeared since the first edition.

As before, the volume is in 3 parts, I, Petrofabric and Experimental Facts; II, Interpretation and Application; III, Methods and Analytic Procedures. Part I includes orientation patterns of minerals, of composite elements, and related to *s*-surfaces; also deformation and recrystallization. Part II includes development of quartz and other mineral orientations, rock flowage, folding, rotation, recrystallization, and tectonic transport.

Numerous diagrams help clarify the text, which, of necessity, is rather difficult reading, because the subject is not a simple one.

It is a book that advanced petrographers will have to own.

Bibliographie des Livres, Thèses et Conférences Relatifs à l'Industrie du Pétrole. By MARTHE AGOUT. Pp. 322; 12 photographs. Standard Française des Pétroles, 82 Avenue des Champs Elysées, Paris, France, 1949.

While making documentation researches the members of the Standard Française des Pétroles had often deplored the lack of a French bibliography dealing with the whole of the petroleum industry, which would have enabled one to find quickly the essential information on any given problem. To remedy this the librarian of the company set to work and the result is this most useful volume.

As the petroleum industry, or at least its commercial development, dates back to the second half of the 19th Century, the author has extended this bibliography over a period of 100 years, 1847–1947, so as to show a brief picture of that industry. It includes the census of all books, theses, lectures, and pamphlets in all languages dealing with the petroleum or auxiliary industries. Wherever possible the author has referred to the original document, and in its absence to the most important and oldest bibliographies.

The 6408 references have been classified as logically as possible under about 400 headings, extracted mostly from the classification used by E. DeGolyer and H. Vance in their "Bibliography on the Petroleum Industry." These 400 headings come under ten major divisions, namely: General Information on the Technology and Industry of Petroleum and Annex Industries; Geographical Distribution of Petroleum—Deposits—Studies; Physical and Chemical Properties of Petroleum—General Methods of Sampling; Surface Exploration and Prospection—Search for Petroleum and Other Natural Hydrocarbides—Geology of Petroleum; Prospecting

and Drilling for Petroleum, Natural Gas and Other Natural Hydrocarbides Deposits; Production of Raw Petroleum, Natural Gas and Natural Hydrocarbides; Transportation, Stocking and Gauging; Treatment of Raw Materials—Procurement of End Products; Utilization of Petroleum Products; Economy of Petroleum and Annex Industries. At the end of the book there are two alphabetical indices, one by authors and the other by subjects.

It is almost impossible to compile such an extensive work without missing out on many references, the more so as for many years the author was unable to receive or consult foreign material. It is nevertheless a very important step in the bibliography of petroleum and invaluable in looking up references relating to the French industry. The author hopes that later, when this edition is exhausted, a more extensive and more complete bibliography may be published. In the meantime this is a most valuable reference book which all interested in the petroleum industry will wish to have, and the author and the Standard Française des Pétroles are to be congratulated.

M. L. MIGNONE.

Applied Sedimentation—A Symposium. Edited by PARKER D. TRASK. Pp. 707; numerous figures and tables. Nat. Research Council. John Wiley & Sons, New York, 1950. Price, $5.00.

This publication results from the Committee on Symposium on Sedimentation of the Division of Geology and Geography of the National Research Council and its 35 chapters are by as many authors under the able editorship of Parker D. Trask. There are seven main topics, with 2 to 10 articles under each, as follows: Basic Principles of Sedimentation; Engineering Problems Involving Strength of Sediments; Applications of Processes of Sedimentation; Applications Involving Nature of Constituents; Economic Mineral Deposits; Petroleum Geology Problems; Military Applications.

All types of sedimentary materials are considered from the most ancient rocks to the youngest, including the various types of soils. All phases of engineering and economic aspects are covered in relation to engineering geology, mining geology, petroleum geology, and theoretical geology, even including chemical prospecting for ores.

The subject matter is of interest to all geologists, with, of course, particular interest to consulting geologists, petroleum geologists, and engineers. Noteworthy in relation to economic geology are the following subjects: Clays in Ceramics, by Ralph E. Grim; Foundry Sands, by H. Ries; Sedimentary Iron Deposits, by S. A. Tyler; Sedimentary Rocks as Hosts for Ore Deposits, by J. S. Brown; Geochemical Prospecting for Ores, by H. E. Hawkes; Porosity, Permeability, and Capillary Properties of Petroleum Reservoirs, by C. D. Russell and P. A. Dickey; Carbonate Porosity and Permeability, by W. C. Imbt; and Sedimentary Materials in Military Geology, by F. C. Whitmore, Jr. Adequate references accompany each paper.

This book should be in every geologist's library.

Introduction to Theoretical Igneous Petrology. By ERNEST E. WAHLSTROM. Pp. 365; numerous figures and tables. John Wiley & Sons, New York, 1950. Price, $6.00.

This compact little book will fill a need for students in geology and petrology. It brings together much of the theoretical knowledge of petrology now to be found only in voluminous books and widely scattered papers in many languages. It is not

an elementary text as it assumes a knowledge of elementary geology, mineralogy, petrology, and mathematics. It deals with the physics and physical chemistry of rocks and rock origins in language that is not too technical to swamp an ordinary student. Certain aspects may appear to be too brief or inconclusive, but numerous chapter references will supply opportunity for further investigation.

The 14 chapters are: Part I, Introduction; Heterogeneous Equilibrium and the Phase Rule; Equilibrium in Silicate Systems; Igneous Minerals; Part II, The Crust and Interior of the Earth; Magmas—Source and Nature; The Ascent and Emplacement of Magmas; Crystallization of Magmas; Igneous Differentiation; Assimilation and Syntexis; Granitization; Late Magmatic and Postmagmatic Processes; Origin of Rock Types; Classification of Igneous Rocks. An Appendix follows on Physical-Chemical Concepts Useful to Petrologists, which the author advises the student to read first.

The economic geologists will be particularly interested in the chapters on magmas, crystallization, differentiation, and late magmatic processes where are found discussions that bear on the problems of magmatic ore deposits.

Numerous equilibrium and ternary diagrams are included to illustrate the physical-chemical discussions.

Who Knows—and What, among Authorities, Experts, and the Specially Informed. Pp. 796. A. N. Marquis Co., Chicago, Ill., 1950. Price, $15.70.

This is a most unusual and novel type of Who's Who. It is built up around an Idea which took several years to develop. It is not a simple directory as in Who's Who in America, but it is a classification of "knowers" in the various fields of thought. It contains a directory, of course, but it is cross-classified by means of a "Locator Index." If one wishes to find those people who are specialists in a given subject, he turns to the locator index, of which there are 43 pages in fine type, and looks under "ants" or "arctic" or "ores" or "planets" and there finds a series of double numbers. The first member refers to the directory page, the second to the number assigned to a specialist. Under the latter may be found the listee's sketch, or a star referring to his sketch in Who's Who in America, or an asterisk indicating that additional data appears in Who's Who. This locator index appears to cover every subject or place, with many subdivisions, that human beings have thought or written about or know about. The Locator Index is the big new Idea. At the end of it is a broader classification of the recognized selected fields, from Agronomy to Zoology. Under "Geology," for example, are 84 sets of numbers, which refer to that many geologists in the directory (although the reviewer found his number omitted from this particular grouping).

"Who Knows—and What" really permits one to find out who are the people who are "knowers" in any field of knowledge. It is, therefore, much more useful than a regular type of Who's Who.

BOOKS RECEIVED.

CHARLES H. SMITH.

U. S. Geological Survey—Washington, D. C., 1949–1950.

Prof. Paper 227. Pegmatite Investigations in Colorado, Wyoming, and Utah, 1942–1944. JOHN B. HANLEY, E. WM. HEINRICH, AND LINCOLN R. PAGE. Pp. 125; pls. 17; figs. 34; tbls. 7. *A report on resources of beryllium, tantalum and lithium minerals and of muscovite. General geology and features of pegmatites, also descriptions of individual pegmatite localities.*

Circ. 74. A Glossary of Uranium- and Thorium-Bearing Minerals. JUDITH WEISS FRONDEL AND MICHAEL FLEISCHER. Pp. 20. *Lists 162 mineral species which are either uranium- and thorium-bearing or contain intergrowths of uranium and thorium.*

Bull. 948-E. Preliminary Report on Corundum Deposits in the Buck Creek Peridotite, Clay County, North Carolina. JARVIS B. HADLEY. Pp. 25; pls. 4; figs. 3; tbls. 3. *Veins and disseminated deposits. Veins are result of hydrothermal replacement of dunite rather than desilication of pegmatite magma. Disseminated corundum contributed to concentration of alumina originally contained in the plagioclase of troctolite.*

Bull. 955-C. Phosphate Deposits of the Deer Creek-Wells Canyon Area, Caribou County, Idaho. CHARLES DEISS. Pp. 50; pls. 3; fig. 1; tbls. 12. *In Phosphoria formation; inferred reserves of phosphate rock in area nearly 120,000,000 tons.*

Bull. 966-D. Geophysical Abstracts 139, October–December 1949. MARY C. RABBITT, V. L. SKITSKY, AND S. T. VESSELOWSKY. Pp. 80. *Nos. 11442 to 11678.*

Bull. 968. Bibliography of North American Geology 1948. EMMA MERTINS THOM, MARJORIE HOOKER, AND RUTH REECE DUNAVEN. Pp. 309.

Selected Russian Papers on Geochemical Prospecting for Ores. TRANSLATED BY V. P. SOKOLOFF AND H. E. HAWKES. Pp. 103; figs. 28. *6 papers: field spectroanalytical laboratory for servicing prospecting parties; water analysis as a means of prospecting for metallic ore deposits; a new luminoscope for field use; geochemical method of prospecting for ore deposits; ionic method of geophysical prospecting; a physicochemical method of prospecting for molybdenum in the semidesert climate of the northern Lake Balkhash area.*

Water Supply Papers.

968-D. Ground-Water Exploration in the Natchitoches Area, Louisiana. J. C. MAHER AND P. H. JONES. Pp. 52; pl. 1; figs. 3; tbls. 5.

1078. Ground-Water Supplies of the Ypsilanti Area, Michigan. C. L. MCGUINNESS, O. F. POINDEXTER, AND E. G. OTTON. Pp. 105; pls. 5; figs. 7; tbls. 13.

1079-A. Ground-Water Resources of Liberty County, Texas. W. H. ALEXANDER, JR., AND S. D. BREEDING. Pp. 61; pl. 1; figs. 4; tbls. 8.

1079-B. Ground-Water Resources of Gregg County, Texas. W. L. BROADHURST AND S. D. BREEDING. Pp. 42; figs. 2; tbls. 7.

1083, 1084, 1088, 1091. Surface Water Supply of the United States 1947. UNDER THE DIRECTION OF C. G. PAULSEN. **Pt. 3. Ohio River Basin.** Pp. 722; fig. 1. **Pt. 4. St. Lawrence River Basin.** Pp. 288; fig. 1. **Pt. 8. Western Gulf of Mexico Basins.** Pp. 336; fig. 1. **Pt. 11. Pacific Slope Basins in California.** Pp. 450; fig. 1.

1099. Water Levels and Artesian Pressure in Observation Wells in the United States in 1947. Pt. 4. South-Central States. UNDER THE DIRECTION OF C. G. PAULSEN. Pp. 201; figs. 12.

1103. Use of Water by Bottom-Land Vegetation in Lower Safford Valley, Arizona. J. S. GATEWOOD, T. W. ROBINSON, B. R. COLBY, J. D. HEM, AND L. C. HALPENNY. Pp. 210; pls. 5; figs. 45; tbls. 59.

1105. Hydrology of Massachusetts. Pt. 1. Summary of Stream Flow and Precipitation Records. C. E. KNOX AND R. M. SOULE. Pp. 240; pl. 1.

Summary of Stratigraphy Shown in Geologic Cross-Section of Illinois Basin. L. E. WORKMAN, D. H. SWANN, AND ELWOOD ATHERTON. Pp. 18; section 1. Illinois Geol. Survey Circ. 160, Urbana, 1950.

Origin of Kansas Great Plains Depressions. JOHN C. FRYE. Pp. 20; pls. 4; figs. 2. Kansas Geol. Survey Bull. 86, Pt. 1, Lawrence, 1950. *Depressions due to solution-subsidence, differential eolian deposition or erosion, compaction, silt infiltration and animal action.*

Revision of the Classification of the Post-Cherokee Pennsylvanian Beds of Missouri. FRANK C. GREENE AND WALTER V. SEARIGHT. Pp. 21; figs. 4. Missouri Geol. Survey Rept. Inves. 11, Rolla, 1949.

List of Publications and Maps on the Geology and Mineral Resources of Ohio. Pp. 16. Ohio Geol. Survey, Columbus, 1950.

Directory of Washington Mining Operations 1950. MARSHALL T. HUNTTING. Pp. 67. Washington Div. Mines and Geology Inf. Circ. 18, Olympia, 1950.

Minerals Yearbook 1947. UNDER THE DIRECTION OF E. W. PEHRSON; ALLAN F. MATTHEWS, EDITOR. Pp. 1616. Washington, D. C., 1949.

Technical Publications 1947. Pp. 499; numerous figures and tables. Standard Oil Co., New Jersey, 1950. *Second annual volume of papers written by associates of Standard Oil Company (New Jersey) and its affiliates. Contains 21 papers under the general headings of geology and production research, manufacturing research, production quality research, and analysis.*

Summer Field Courses in Geology 1950. Pp. 101. Am. Geol. Inst. Rept. 1, Washington, D. C., April 1950. *Describes the field courses offered by 79 colleges and universities under the following headings: location, date, geology, instruction, report, faculty, facilities, cost, registration and other information.*

Reference Clay Localities—Europe. RALPH JEROME HOLMES. Pp. 101; figs. 27. Am. Petrol. Inst. Project 49, Clay Mineral Standards, Prel. Rept. 4, Columbia Univ., New York, 1950. *Geology and theories of origin of 17 clay localities in Scotland, England, Wales, France and Germany described.*

Ontario Department of Mines—Toronto, 1950.

57th Annual Report, Vol. LVII, Pt. V, 1948. Pp. 196; figs. 62; tbls. 12; 20 colored maps and sections. **Geology of Teck Township and the Kenogami Lake Area, Kirkland Lake Gold Belt.** JAS. E. THOMSON. *Part of a detailed investigation of the entire Kirkland Lake-Larder Lake gold belt.* **Geology of the Main Ore Zone at Kirkland Lake.** JAS. E. THOMSON AND OTHERS. *Deals with the underground geology of the seven producing mines along the Kirkland Lake "break."*

Prel. Rept. 1950–5. Geology of Part of Township 29, Range XIV, District of Algoma. E. W. NUFFIELD. Pp. 6; maps 2. *Area contains radioactive minerals in granite, pegmatite and in or near diabase.*

Ind. Mineral Circ. 1. Asbestos in Ontario. D. F. HEWITT. Pp. 7.

SCIENTIFIC NOTES AND NEWS

C. E. B. CONYBEARE, former assistant professor of geology at the University of Manitoba, has accepted a position as petrologist with the U. S. Geological Survey and will be attached to the Geological Survey of Gold Coast at Saltpond, Gold Coast, West Africa.

A new geochemical journal, "Geochimica et Cosmochimica Acta," is being published by Butterworth-Springer, 436 Strand, London, W. C. 2, England, under the editorship of Prof. L. R. Wager. The journal is interenational in scope and the plan is to give prompt publication to geochemical papers from all over the world. They will be published in English, French or German, with English summaries. Authors are to be given 75 reprints free of charge. Manuscripts should be sent to Earl Ingerson, U. S. Geological Survey, Washington 25, D. C., who is American editor for the new publication. Subscription prices have not yet been announced, but the American agent is the Academic Press, Inc., 125 East 23rd Street, New York 10, New York, to whom inquiries should be addressed.

WILLIAM JOHN PUGH, Professor of Geology and Deputy Vice-Chancellor in the Victoria University of Manchester, has been appointed to be Director of the Geological Survey and Museum of Practical Geology in the Department of Scientific and Industrial Research, and will take up his new appointment this autumn.

DAVID WILLIAMS has been appointed Professor of Mining Geology in the University of London in respect of his position at the Royal School of Mines.

A. W. JOLLIFFE has resigned as Associate Professor in Geology at McGill University to become Professor in the Department of Geology at Queens University, Kingston, Ontario.

ATHELSTAN SPILHAUS, Dean of the Institute of Technology, University of Minnesota, has been named Deputy Chairman of the Committee on Geophysics and Geography of the Research and Development Board, Department of Defense, to succeed Dr. W. W. Rubey of the U. S. Geological Survey.

Professor Spilhaus, who has served as an alternate member of the committee since its formation in December, 1948, is one of five civilian members who serve on the committee. Dr. W. E. Wrather, Director of the Geological Survey, is chairman, and other civilian members are Dr. P. E. James, Professor of Geography, Syracuse University, Syracuse, N. Y.; Dr. Horace Byers, Department of Meteorology, University of Chicago; Samuel B. Morris, General Manager and Chief Engineer, Department of Water and Power, Los Angeles, California; Dr. Richard Joel Russell, School of Geology, Louisiana State University, Baton Rouge. Two representatives each from the Army, Navy, and Air Force complete the membership of the committee. Dr. H. E. Landsberg is executive director of the committee secretariat which has its headquarters in the Pentagon.

ALCOA MINING COMPANY announces that since May 31 Ernest A. Messer, for the past five years resident engineer in charge of their Oregon activities, has resigned his position with Alcoa Mining Company to enter private consulting work.

Alcoa Mining Company will continue geological investigations in this and other western areas. This work and the Company's laboratory and office in Hillsboro will be under the general supervision of Jack H. McWilliams.

WALLACE E. PRATT has been awarded the James Furman Kemp Medal for distinguished service in geology by the faculty of Columbia University. The presentation was made by President Eisenhower at Columbia on the evening of May 4th.

DUNCAN MCCONNELL has accepted a position as professor of mineralogy at the Ohio State University and is leaving the employment of the Gulf Research & Development Co.

At Columbia University the Department of Geology, continuing its policy of rotating administrative duties, has elected Prof. Walter H. Bucher to serve as Executive Officer for a period of three years. He succeeds Prof. Paul F. Kerr whose term expired on June 30, 1950, and who held office during the difficult period of post-war reconstruction. Prof. Marshall Kay has been elected Educational Coordinator and Prof. Kerr Research Coordinator. These three will constitute an Executive Committee for the Department.

The Fall Regional Meeting of the Industrial Minerals Division, A.I.M.E., is to be held in Norman, Oklahoma, October 17–20. Host for the meeting will be the Oklahoma Geological Survey; Dr. Robert H. Dott, Director of the Survey, is chairman of the local committee. October 17 and 18 will be devoted to technical papers which will highlight industrial mineral developments of the Southwest. Following this a two-day field trip in the Arbuckle Mountain area will be led by W. E. Ham of the Oklahoma Geological Survey to visit active glass sand, dolomite, limestone, asphalt, and cement operations, other industrial mineral deposits and points of geologic interest. Dr. Hugh D. Miser, U. S. Geological Survey, noted for tales of his native Arkansas hill country, will speak at a dinner meeting on October 17. His subject will be "Making a Geologic Map of Oklahoma"—a project in which he is currently engaged. The Norman meeting is the first to be held in this general area and promises a varied fare of interest to people engaged in all phases of industrial mineral production.

The Alberta Society of Petroleum Geologists will be hosts at a Regional Meeting of the American Association of Petroleum Geologists to be held jointly with the Society of Exploration Geophysicists and the Geological Association of Canada at the Banff Springs Hotel, September 5 to 8, 1950.

JOSEPH W. MILLS has resigned as resident geologist for the O'Brien Gold Mines, Ltd., Kewagama, Quebec, to accept an appointment as assistant professor in economic geology at the State College of Washington at Pullman.